h e p i a
Haute école du paysage, d'ingénierie
et d'architecture de Genève

Hes·SO
Haute Ecole Spécialisée
de Suisse occidentale

« The evaluation of agroforestry systems in Robusta coffee plantations in the Amazonian Ecuadorian Region with respect to pests and diseases »

(Source: Kevin Piato)

STRICTLY CONFIDENTIAL STUDY

Bachelor thesis presented by:

Kevin PIATO

In completion of the HES-SO Bachelor's degree of Science in Agronomy

November 2018

HES Supervising Professor
Prof. François Lefort

Supervisor
Cristian Subía García

Head of Agronomy Department
Sophie Rochefort

Déclaration

Ce travail de Bachelor est réalisé dans le cadre de l'examen final de la Haute École du paysage, d'ingénierie et d'architecture de Genève, en vue de l'obtention du titre de Bachelor HES en Agronomie.

L'étudiant assume la responsabilité du travail et accepte, le cas échéant, la clause de confidentialité. Par contre, les conclusions et les recommandations qu'il y formule, sans préjuger de leur valeur, n'engagent ni les responsabilités de l'auteur, ni celle du Prof. HES responsable TB ni celle du superviseur, des experts et de hepia.

« J'atteste avoir réalisé seul le présent travail, sans avoir utilisé des sources autres que celles citées dans la bibliographie »

Fait à Joya de las Sachas, le 20 septembre 2018

Kevin PIATO

Acknowledgments

The author would like to thank Dr François Lefort and Nicole Chavaz at hepia (Geneva School of Engineering, Architecture and Landscape), Cristian Subía García and his colleagues at INIAP (Instituto Nacional de Investigaciones Agropecuarias) and Jeffrey Caraballo-Ferrer at CTAHR (Hawai'i College of Tropical Agriculture and Human Resources) for their scientific and technical support. The author would also like to thank Aline Junod, Antonia Frei, Holly Masterson and Christine Armfield who have revised the English of the present thesis.

Summary

This thesis presents a study that aims to evaluate the effects of shading and different farming practices on pest and disease development on Robusta coffee trees situated in Joya de las Sachas, in the Ecuadorian Amazon region. This trial has allowed comparison between different agroforestry systems (combining a shading method with a farming practice) in terms of pest and disease development on Robusta coffee. Nine response variables have been evaluated on Robusta coffee: *Xylosandrus morigerus* infestation, *Leucoptera coffeella* infestation, *Hypothenemus hampei* infestation, *Colletotrichum spp*. incidence and severity, *Pellicularia koleroga* incidence, *Cercospora coffeicola* incidence, *Phoma spp*. incidence and *Beauveria bassiana* presence. The five coffee shading methods assessed were: full sunlight, *Myroxylon balsamum* with *Musa spp*., *Inga edulis* with *Musa spp*., *Erythrina spp*. with *Musa spp*. and the combination of *Erythrina spp*., *Myroxylon balsamum* and *Musa spp*. The four coffee farming practices assessed were: intensive conventional, moderate conventional, intensive organic and low organic. All the variables were evaluated monthly in July, August and September 2018, according to a split-block design with three replications, the shading method as the main plot and the farming practice as the subplot. The mentioned pest and disease assessments were mainly based on the INIAP protocol (Instituto Nacional de Investigaciones Agropecuarias) for crop health characterisation. *Colletotrichum ssp*. severity was determined by using the ImageJ programme.

Furthermore, the study aims to quantify the shade percentage of each of the five shading methods assessed and to compare them. To that end, under each shading method solar radiation was measured on the coffee plants with a pyranometer, according to a randomised complete blocks design with four replications. The shade percentage was worked out by comparing solar radiation under the canopy to that in full sun conditions. Our most important results show that when Robusta coffee plants are intercropped with *Inga edulis* trees, *Xylosandrus morigerus* infestation is reduced to less than 9%, as compared to Robusta coffee plants in full sun. We also found that organic farming practices show a *Xylosandrus morigerus* infestation of less than 12% as compared to conventional farming practices. Also worth noting is the fact that conventional farming practices present a higher *Hypothenemus hampei* infestation (up to 12% higher) and *Beauveria bassiana* presence is up to 17% higher than with organic farming practices. However, *Colletotrichum spp*. severity was found to be greater with organic farming practices (up to 3% higher) than with conventional ones. For the shading methods *Myroxylon balsamum* with *Musa spp*., *Inga edulis* with *Musa spp*., *Erythrina spp*. with *Musa spp*. and the combination of *Erythrina spp*., *Myroxylon balsamum* and *Musa spp*., the shade percentages were respectively: 15.1%, 26.4%, 29.8% and 9.2%. It appears from the results that farming practices had a more notable impact on pest and disease

development than shading methods, due to the trees being too small (1-3 years old) and slightly defoliated, therefore not providing uniform shade within the whole plot. Further research is needed with more developed shelter trees or a higher density per hectare.

Résumé

L'étude présentée a pour but d'évaluer l'impact de l'ombrage et de différents modes de production sur le développement de maladies et ravageurs de caféiers robusta situés à Joya de los Sachas en Amazonie équatorienne. L'étude proposée permet ainsi de comparer l'effet de différents systèmes agroforestiers sur l'état phytosanitaire de caféiers robusta. 9 variables réponses ont été évaluées : les infestations de *Xylosandrus morigerus*, *Leucoptera coffeella* et *Hypothenemus hampei*, l'incidence et la sévérité de *Colletotrichum spp.*, les incidences de *Pellicularia koleroga*, *Cercospora coffeicola*, *Phoma spp*. ainsi que la présence de *Beauveria bassiana*. Cinq types d'ombrage ont été évalués : plein soleil, *Myroxylon balsamum* avec *Musa spp*., *Inga edulis* avec *Musa spp*., *Erythrina spp*. avec *Musa spp*. et la combinaison d'*Erythrina spp*., *Myroxylon balsamum* et *Musa spp*. 4 modes de production ont été évalués : conventionnel intensif, conventionnel atténué, biologique intensif et biologique avec faible intervention. Toutes les variables ont été évaluées en juillet, août et septembre 2018, selon un dispositif en bandes croisées avec 3 répétitions, le type d'ombrage en grande parcelle et le mode de production en petite parcelle. Les évaluations phytosanitaires ont été faites selon le protocole de l'INIAP (Instituto Nacional de Investigaciones Agropecuarias) en Equateur. La sévérité de *Colletotrichum spp*. a été déterminée à partir du programme ImageJ. L'étude présentée s'est également donnée pour but de quantifier l'ombrage apporté par chacun des 5 types d'ombrage aux caféiers et de les comparer entre eux. Pour cela, un pyranomètre a été utilisé afin de mesurer la radiation solaire totale arrivant sur les caféiers selon un dispositif en 4 blocs aléatoires complets. Le % d'ombrage a été calculé en comparant la quantité de radiation solaire sous la canopée des arbres avec celle en plein soleil. Les résultats les plus importants trouvés révèlent que l'association des caféiers avec l'arbre *Inga edulis* permet de réduire jusqu'à 9% l'infestation de *Xylosandrus morigerus* par rapport au système plein soleil et que les modes de production biologique permettent de réduire jusqu'à 12% l'infestation du même ravageur en comparaison avec les modes de production conventionnelle. En plus, il est obtenu une infestation par *Hypothenemus hampei* jusqu'à 12% supérieure et une présence du champignon *Beauveria bassiana* jusqu'à 17% supérieure avec les modes de production conventionnelle par rapport aux modes de production biologique. La sévérité de *Colletotrichum spp*. a été plus importante dans les parcelles avec les modes de production biologiques (jusqu'à 3% supérieure) qu'avec les modes de production conventionnelle. Les % d'ombrage trouvés pour les méthodes d'ombrage *Myroxylon balsamum* avec *Musa spp*., *Inga edulis* avec *Musa spp*., *Erythrina spp*. avec *Musa spp*. et la combinaison d'*Erythrina spp*., *Myroxylon balsamum* et *Musa spp.* ont été respectivement de 15.1%, 26.4%, 29.8% et 9.2%. Il ressort des résultats que le mode de production a plus influencé les variables phytosanitaires que le type d'ombrage. Ceci

pourrait s'expliquer par le jeune âge des arbres plantés (1-3 ans) qui pour la plupart sont légèrement défoliés, facteurs ne permettant pas d'obtenir un ombrage homogène sur l'ensemble de la parcelle. Des recherches avec des arbres plus développés sont nécessaires ou avec des densités de plantations d'arbre plus importantes.

Zusammenfassung

Die vorgelegte Studie verfolgt das Ziel, die Schattenwirkung und verschiedene landwirtschaftliche Verfahren über die Entwicklungen von Schädlingen und Krankheiten des Robusta Kaffeeanbaus zu bewerten. Das Experiment fand in Joya de los Sachas im Amazonasgebiet Ecuadors statt. Die vorgelegte Studie ermöglicht somit den Vergleich von verschiedenen Agrarfortsystemen auf die Pflanzengesundheit von Robusta Kaffeestrauch. 9 Reaktionsvariablen wurden bewertet: die Befälle von *Xylosandrus morigerus*, *Leucoptera coffeella* und *Hypothenemus hampei*, die Inzidenz und der Schweregrad von *Colletotrichum spp*., die Inzidenzen von *Pellicularia koleroga*, *Cercospora coffeicola*, *Phoma ssp*. und die Präsenz von *Beauveria bassiana*. 5 verschiedene Beschattungen wurden bewertet: pralle Sonne, *Myroxylon balsamum* mit *Musa spp*., *Inga edulis* mit *Musa spp*., *Erythrina spp*. mit *Musa spp*. und die Kombination von Erythrina spp., *Myroxylon balsamum* und *Musa spp*. 4 landwirtschaftliche Verfahren wurden bewertet: konventionell intensiv, konventionell abgeschwächt, biologisch intensiv, biologisch mit geringer Intervention. Alle Variablen wurden im Juli, August und September 2018 bewertet gemäss Split-Plot-Versuchsplan mit 3 Repetitionen, das Verfahren von Beschattung im grossen Grundstück und die landwirtschaftlichen Verfahren im kleinen Grundstück. Die pflanzengesundheitlichen Bewertungen wurden gemäss dem Protokoll von INIAP (Instituto Nacional de Investigaciones Agropecuarias) in Ecuador durchgeführt. Der Schweregrad von *Colletotrichum spp*. wurden mit dem Programm ImageJ festgelegt. Die vorgelegte Studie verfolgt auch das Ziel die 5 Verfahren von Beschattungen zu quantizieren und zu vergleichen. Zu diesem Zweck, ein Pyranometer wurde genutzt um die gesamte Sonnenstrahlung auf den Robusta Kaffeesträucher gemäss einem randomisierten vollständiges Blockanlagen mit 4 Repetitionen zu verzeichnen. Die prozentuale Beschattung wurde durch den Vergleich zwischen der Sonnenstrahlung unter dem Baumkronendach und die Sonnenstrahlung in der prallen Sonne berechnet. Die wichtigsten erzielten Ergebnisse zeigen, dass die Kombination von Robusta Kaffeesträucher mit dem *Inga edulis* Bäumer bis 9% den Befall von *Xylosandrus morigerus* gegenüber den Robusta Kaffeesträuchern in der prallen Sonne verringert. Die biologischen landwirtschaftlichen Verfahren verringern bis 12% den Befall von *Xylosandrus morigerus* gegenüber den konventionellen landwirtschaftlichen Verfahren. Zusätzlich, die biologischen landwirtschaftlichen Verfahren verringern bis 12% den Befall von *Hypothenemus hampei* und die Präsenz von *Beauveria bassiana* bis 17% gegenüber den konventionellen landwirtschaftlichen Verfahren. Der Schweregrad von *Colletotrichum spp*. war höher (3% mehr) mit den biologischen landwirtschaftlichen Verfahren gegenüber den konventionellen landwirtschaftlichen Verfahren. Die erzielten prozentualen Beschattungen für die verschiedenen Beschattungen *Myroxylon balsamum* mit *Musa spp*., *Inga edulis* mit

Musa spp., *Erythrina spp*. mit *Musa spp*. und die Kombination von *Erythrina spp*., *Myroxylon balsamum* und *Musa spp.* waren beziehungsweise von 15.1%, 26.4%, 29.8% und 9.2%. Die Ergebnisse zeigen, dass die landwirtschaftlichen Verfahren mehr als die Beschattungen, die pflanzengesundheitliche Variablen beeinflusst haben. Dies lässt daraus schliessen, dass die für die Beschattung genützen Baüme zu jung (1-3 Jahren) und schwach verlichtet waren. Daher war die Beschattung nicht gleichmässig auf die Versuchseinheiten verteilt. Weitere Untersuchungen mit älteren Bäumen oder mit einer höheren Pflanzdichte sind erforderlich.

Resumen

Este estudio tiene como objetivo evaluar el impacto de la sombra y de diferentes manejos agronómicos sobre el desarrollo de enfermedades y plagas en el cultivo de café robusta bajo sistemas agroforestales en la Estación Experimental Central de la Amazonía (EECA) del Instituto Nacional de Investigaciones Agropecuarias (INIAP) ubicado en el cantón La Joya de los Sachas, provincia de Orellana en la Amazonía ecuatoriana. De esta manera, el estudio permitió comparar el estado fitosanitario de plantas de café robusta. Se evaluaron nueve variables de respuesta que son las siguientes : porcentaje de infestación de *Xylosandrus morigerus*, *Leucoptera coffeella* y *Hypothenemus hampei*; la incidencia y severidad de *Colletotrichum* spp., la incidencia de *Pellicularia koleroga*, *Cercospora coffeicola*, *Phoma* spp. y la presencia de *Beauveria bassiana* en los frutos del café. Los factores en estudio fueron los arreglos agroforestales y los tipos de manejo. Los arreglos agroforestales o tipos de sombra fueron: libre exposición solar, *Myroxylon balsamum* + *Musa* spp., *Inga edulis* + *Musa* spp., *Erythrina* spp. + *Musa* spp. y *Erythrina spp*. + *Myroxylon balsamum* + *Musa* spp. Además se evaluaron cuatro manejos agronómicos : alto convencional, medio convencional, orgánico intensivo y bajo orgánico. Se evaluaron las variables en los meses de julio, agosto y septiembre de 2018, bajo un diseño de bloques completos al azar con 3 repeticiones en arreglo de franjas donde el tipo de sombra corresponde a las columnas y el tipo de manejo agronómico a las filas. El cruce de los niveles de los factores corresponde a los tratamientos o sistemas agroforestales (5x4 = 20). Las evaluaciones fitosanitarias se realizaron de acuerdo al protocolo del INIAP de Ecuador. Para la severidad de *Colletotrichum* spp. se utilizó el programa ImageJ. La cantidad de sombra sobre las plantas de café resultó de la presencia de las diferentes especies componentes de los arreglos agroforestales, la misma que fue cuantificada y comparada, para lo que se utilizó el pyranómetro que mide la radiación solar total que llega sobre las plantas de café y se analizó bajo un diseño de 4 bloques aleatorios completos. Se calculó el porcentaje de sombra comparando el promedio ponderado dentro de cada sistema con la cantidad de radiación solar a libre exposición. Los resultados más importantes mostraron que la asociación del café robusta con el árbol *Inga edulis* permitió reducir hasta el 9% de infestación de *Xylosandrus morigerus* respecto de las plantas de café en libre exposición solar. Además, los manejos orgánicos permiten reducir hasta en un 12% la infestación de *Xylosandrus morigerus* en comparación con los manejos convencionales. En los manejos convencionales la infestación de *Hypothenemus hampei* fue mayor en un 12% y mayor presencia del hongo *Beauveria bassiana* hasta en un 17%, respecto de los manejos orgánicos. La severidad de *Colletotrichum* spp. fue importante en las parcelas con los manejos orgánicos (hasta 3% más) comparado con los manejos convencionales. Los porcentajes

de sombra obtenidos para los arreglos agroforestales con *Myroxylon balsamum* + *Musa* spp., *Inga edulis* + *Musa* spp., *Erythrina* spp. + *Musa* spp. y *Erythrina* spp. + *Myroxylon balsamum* + *Musa* spp. fueron de 15.1, 26.4, 29.8 y 9.2%. Los resultados mostraron que el manejo agronómico influye más sobre las variables fitosanitarias que el tipo de sombra. Esto puede ser explicado por la edad muy joven de los árboles de sombra (1-3 años) y también porque muchos árboles tienen hojas dañadas por plagas, lo que no permitió obtener una sombra completa sobre la parcela neta. Es necesario continuar con la investigación para evaluar la sombra con los árboles más desarollados o realizar investigaciones con mayor densidad de árboles para tener resultados más relevantes respecto del tipo de sombra.

Contents

List of Tables

List of Figures

List of Pictures

List of Abbreviations

AFS: agroforestry systems
ALSC: American leaf spot of coffee (*Mycena citricolor*)
BB: *Beauveria bassiana*
BCTB: Black coffee twig borer (*Xylosandrus compactus*)
BTB: Brown twig beetle (*Xylosandrus morigerus*)
CATIE: Centro Agronómico Tropical de Investigación y Enseñanza (Costa Rica)
CBB: Coffee berry borer (*Hypothenemus hampei*)
CBD: Coffee berry disease (caused by *Colletotrichum kahawae*)
CS: *Colletotrichum spp.*
CIFC: Centro de Investigaçao das Ferrugens do Cafeeiro (Portugal)
CLM: Coffee leaf miner (*Leucoptera coffeella*)
CLR: Coffee leaf rust (*Hemileia vastatrix*)
CLS: Cercospora leaf spot (*Cercospora coffeicola*)
CTB: Coffee twig borer (*Xylotrechus quadripes*)
EAR: Ecuadorian Amazon region
EECA:: Estación Experimental Central de la Amazonía (Ecuador)
e.g.: for example, from latin “exempli gratia”
ERY: Erythrina service
ES: *Erythrina spp.*
GUA: Guaba service
IC: Intensive conventional
ICAFE: Instituto del Café de Costa Rica
ICO: International Coffee Organization
i.e. : in other words, from latin “id est”
INIAP: Instituto Nacional de Investigaciones Agropecuarias (Ecuador)
IPCC: Intergovernmental Panel on Climate Change
IO: Intensive organic

IE: *Inga edulis*
LMM: linear mixed models
LO: Low organic
MAS: marker-assisted selection
masl: metres above sea level
MB: *Myroxylon balsamum* (L.)
MC: Moderate conventional
PDD: pest and disease development
PS: *Phoma spp*.
QTLs: quantitative trait loci
SUN: Full sun
RH: relative humidity
TaE: Timber and Erythrina service
TB: Thread blight (*Pellicularia koleroga*)
TIM: Timber
WCB: White coffee borer (*Monochamus leuconotus*)

Introduction: context and objectives

In terms of monetary value, coffee is only surpassed by petroleum (Illy, 2002). Currently, however, global coffee plantation productivity is severely threatened by both climate change, including overall drought (DaMatta and Ramalho, 2006), and a lower revenue for coffee growers due to recent overproduction years. These two factors cause socio-economical problems and concern about 100 million people in the world. Furthermore, in a climatic context which favours the outbreak of pests and diseases, coffee growers are dependent on levels of input to grow their coffee crops and this increases their precariousness. This dependence on inputs is the result of most coffee plantations being full-sun exposed, whereas the most cultivated species of *Coffea canephora* and *Coffea arabica* are able to grow naturally in shaded conditions. Shade-grown coffee crops are now widely studied since this type of crop system can provide greater sustainability for both crops and the environment (Bedimo et al., 2012). Especially in tropical regions, where farmers are generally poor, coffee agroforestry systems (AFS) could potentially reconcile agricultural, social and environmental goals (Alves et al., 2016).

Shade can both modify microclimates in coffee fields, including the relevant interaction between these modified microclimates, and pest and disease development (PDD). This has been thoroughly documented for Arabica coffee plants (Schroth et al., 2000), but not for Robusta coffee plants. More research is needed to determine how much shade is required to provide the best PDD control (Atallah et al., 2018) and, above all, to determine all the site-specific and crop management conditions which can modify shade effects, thus providing quantitative knowledge of these variations (Liebig, 2017).

The trial presented falls within this context, such as conducted in the framework of the Ecuadorian agronomical research institute INIAP (Instituto Nacional de Investigaciones Agropecuarias). The goals of the proposed trial, located in the Ecuadorian Amazon region (EAR), were the assessment of PDD on Robusta coffee under different AFS associating 5 shading methods with 4 farming practices, and to calculate the shade percentage for each shading method assessed, defined as the quantity of total solar radiation in W/m^2 which cannot reach the coffee plants since it is absorbed or reflected by the overstory trees. After a brief overview of the coffee plant, its main pests and diseases, the challenges faced when growing it and its economic importance, the functions of coffee AFS will be discussed along with their impact on PDD. Then the materials and methods of the trial carried through will be exposed, followed by the results obtained. Finally, the most promising results will be discussed with a view to proposing improvements for further related studies.

1. Genus *Coffea* and its cultivated species

1.1 Botany

The Rubiaceae family has some 500 genera and over 6000 species found mainly as trees and shrubs. This family includes several tropical shrubs, such as *Cinchona spp*., providing the well-known drug quinine, *Rubia tinctoria* providing a dye madder, and *Psychotria ipecacuanha*, from whose roots ipecac is extracted to be used in the treatment of dysentery. The genus *Coffea* belongs to this family and is by far the most economically important genus in the Rubiaceae family (Wrigley, 1988). Two main species dominate, *Coffea arabica* and *Coffea canephora*, forming 99% of the world's coffee production. Two species, *Coffea excelsa* and *Coffea liberica,* cover only approximately 1% of the world's production and are mainly restricted to West Africa and Asia (Wintgens, 2012). According to the author, the number of species belonging to the genus *Coffea* ranges from 25 to 100 (Wrigley, 1988). *Coffea* species are not easy to distinguish but Table 1 gives an approximate morphological key that discriminates the two major coffee species *Coffea canephora* and *Coffea arabica,* and the minor coffee species *Coffea liberica*.

Table 1: Morphological key to distinguish *Coffea arabica*, *Coffea canephora* and *Coffea liberica*

1.	Stipules obtuse or occasionally acute, rarely apiculate; apex of leaves obtuse, rounded and shortly acuminate or rarely acute; domatia usually situated across the base of the lateral nerves or occasionally in the nerve axils……………………………………………………………*Coffea liberica*
1.	Stipules apiculate or aristate or occasionally acute; apices of leaves distinctly acuminate; domatia absent or situated in the nerve axils…………………………..*Coffea arabica* or *Coffea canephora* (2)
2.	Bracteoles bearing large sub foliaceous lobes (up to 2.2 cm long); pedicels usually very short, so that calyces do not exceed the bracteoles at anthesis; leaves 12-35 (-40) cm long; lateral nerves in (8-)11-15(-17) main pairs; domatia absent or pubescent; flowers 5-6(-7)-merous………………………………………………………………………………*Coffea canephora*
2.	Bracteoles bearing smaller sub foliaceous lobes (not exceeding 0.5 cm long); pedicels 1-2(-3) mm long, so that calyces exceed the bracteoles at anthesis; leaves 7-18 cm long; lateral nerves in 7-10 main pairs; domatia glabrous or rarely ciliate, sometimes absent; flowers (4-)5(-6)-merous………………………………………………………………………………………*Coffea arabica*

(Wrigley, 1988)

Table 2 provides the main distinctions between Arabica coffee trees and Robusta coffee trees according to the studies of Clifford and Willson (1985), Wrigley (1988) and Illy (2005).

Table 2: Main distinctions between *Coffea arabica* and *Coffea canephora*

Title	*Coffea arabica*	*Coffea canephora*
Main variety	'Typica'	'Robusta'
Chromosomes (2n)	44	22
Pollination of plant	self-pollinating	cross pollinating
Time from blooming to ripening	9 months	10-11 months
Blooming	after rain	irregularly
Trees per 1ha (on an average)	2500-3300 trees	1250-2500 trees
Productivity (ha)	1500-3000kg	2300-4000kg
Root system	deep	low
Leaf	small and oval	big and wide
Length of the fruit	15mm	12mm
Ripe berries	drop down	stay on the branches
Average temperature	18-22°C	22-28°C
Rainfall in a year	1400-2500mm	2000-2500mm
Altitude	800-2500 masl	0-700 masl
Caffeine content	0.8-1.4%	1.7-4.0%
Taste qualities	sweet, berryish	woody, bitter, plump
Seeds	big, oval, green	tiny, stubby, yellowish
Hemileia vastratrix	receptive	resistant
Pellicularia koleroga	receptive	tolerant
Nematodes	receptive	resistant
Colletotrichum kahawae	receptive	resistant

(Data collected from Clifford and Wilson, 1985, Wrigley, 1988 and Illy, 2005)

The two main cultivated varieties of *Coffea arabica* are 'Typica' and 'Bourbon'. The 'Typica' variety was first cultivated in Yemen and its primary fruiting branches grow horizontally with the addition of narrow leaves. When they are young, the leaves can be pendulous and coppery (Waller et al., 2007). 'Typica' is the oldest variety of Arabica coffee and is susceptible to all main pests, diseases and nematodes; however, it does provide a good cup quality (i.e. the taste of coffee as a beverage) (Feil, 2011; Wintgens, 2012). This variety is still grown in Colombia, Central America, the Caribbean region, Papua New Guinea, The Pacific, Indonesia and Cameroon (Eskes and Leroy, 2012).

The 'Bourbon' variety is a spontaneous 'Typica' mutant double-recessive and was planted by the French in the Bourbon island (nowadays called Réunion) in 1703. It is also plausible that this plant could originate from Yemen (Feil, 2011). When compared with the 'Typica' variety, the 'Bourbon' variety coffee tree has primary fruiting branches which form an acute angle with the stem. It has young leaves which are green (Waller et al., 2007) and broader, rounder drupes and a stiffer main stem and branches (Eskes and Leroy, 2012). Furthermore, the 'Bourbon' variety yields 20-30% more than the 'Typica' variety (Feil, 2011). This variety is still grown in Colombia, Central America and East Africa.

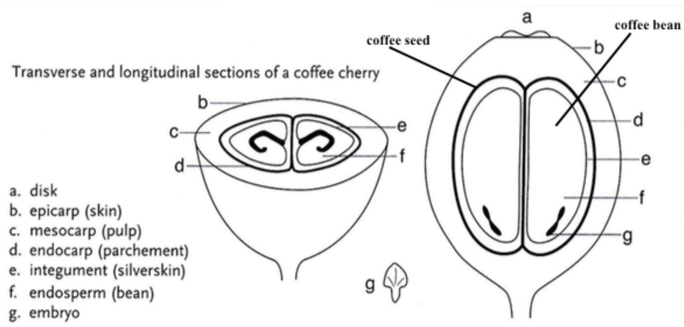
There are two other Arabica varieties which are widely used in Latin America: ‘Caturra’ and ‘Catuai’. The ‘Caturra’ variety is a dwarf mutant of the ‘Bourbon’ variety most commonly found in Brazil. With a high yield potential (over 2000kg/ha), it is well adapted to the growing conditions in Colombia, Costa Rica and Nicaragua, where it can be planted very closely (5000-10000 plants/ha). The ‘Catuai’ variety is a dwarf selected in Brazil, where this variety occupied about 50% of all Brazilian coffee plantations in the 1950s and 1960s. This variety has a higher productivity than ‘Caturra’, as it is produced from a cross between ‘Yellow Caturra’ and ‘Mundo Novo’. This variety, however, needs to receive the correct fertilisation in order to give the best results (Feil, 2011; Eskes and Leroy, 2012).

Since Robusta coffee is cross-fertilised, it presents a high phenotypic variability. The genetic diversity of *Coffea canephora* is divided into two groups: the Congolese and the Guinean groups. Only a small part of this genetic diversity is used in breeding programmes (Loor et al., 2017). The main commercial varieties of *Coffea canephora* include the BP and SA series in Indonesia, which were developed in Java in the 1920s; the S274 and BR series in India, selected from Java’s plant material; the IF series in the Ivory Coast, selected from Java plant material and DR Congo. In Brazil, ‘Apoata’ and ‘Kouilou’ or ‘Conilon’ varieties are used. The ‘Conilon’ variety accounts for about 95% of Robusta coffee plants in Brazil (Illy, 2005). In Ecuador, the last Robusta coffee genetic materials introduced were *Coffea canephora* ‘Conilon’, *Coffea canephora* ‘Robusta’ and *Coffea canephora* ‘Robusta tropical’ (Calderón et al., 2014).

1.2 Biology

Coffee plants take approximately 3-5 years from seed germination to first fruit production. A well-managed coffee plant can be productive for up to 80 years, but the economic lifespan is generally less than 30 years (Wintgens, 2012).

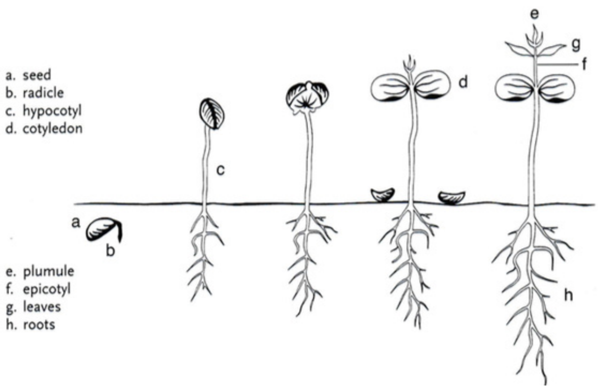
Figure 1. Inner structure of a coffee cherry



(Source: Wintgens, 2012)

The coffee beans, however, are the most important part of the plant, since they are used to produce the coffee beverage. Coffee beans are coffee seeds without the parchment and the silver skin (Figure 1). The size of coffee seeds varies from one coffee variety to another; a parchment seed of Arabica coffee at 18% moisture has a weight of 0.45-0.5 g and that of Robusta coffee weighs 0.37-0.4 g. The coffee seeds do not need a period of dormancy and have an epigeous germination as shown in Figure 3. After sowing, it takes 3 months to obtain the first true leaves.

Figure 3. Germination of a coffee seed



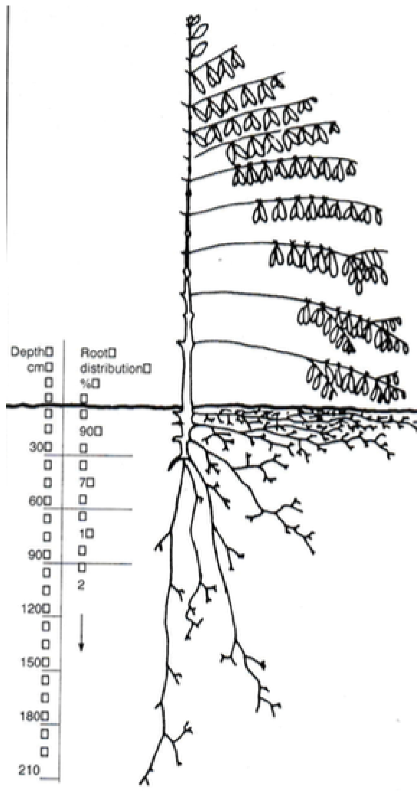
(Source: Wintgens, 2012)

The coffee root system develops mainly in the upper 30 cm layer, where 90% of the root system is located (Figure 2). It is therefore important that this upper layer should contain enough nutrients for roots to develop correctly.

With regard to the framework of the tree, the main stem has an orthotropic development and the branches a plagiotropic development. In both the lateral branches and the main stem, 2 types of buds are present: the “head of series“, which can generate only a plagiotropic stem and the serial buds, which can generate either orthotropic stems or flowers (Figure 4) (Wintgens, 2012).

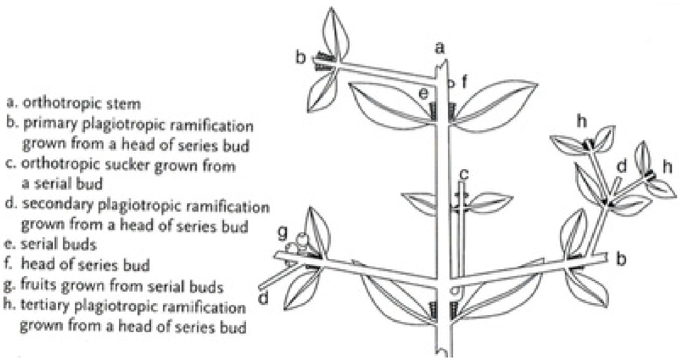
The leaves grow on a petiole in opposite pairs and are dark green in colour, shiny, waxed, have an elliptical shape and conspicuous veins.

Figure 2. Distribution of the root system of a coffee tree



(Source: Wintgens, 2012)

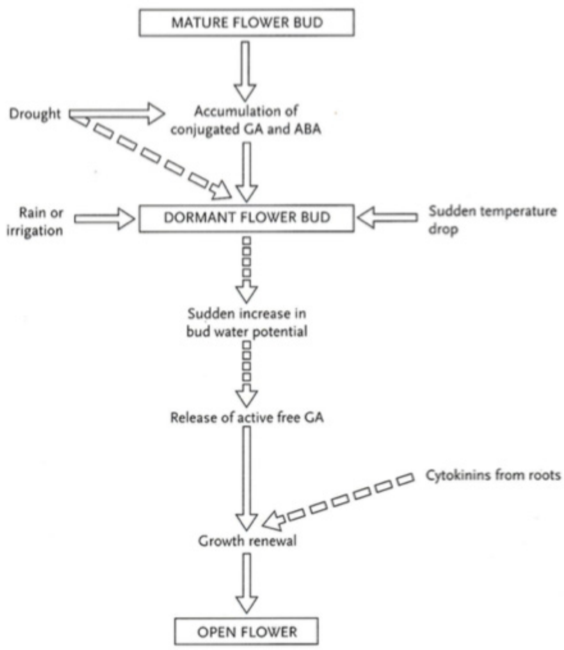
Figure 4. Shoots and buds of a coffee plant



(Source: Wintgens, 2012)

With regard to the flower, the ovary contains 2 ovules which will produce 2 beans if they are duly fertilised. The pollen of coffee flowers is light and easily carried by the wind, especially for Robusta coffee plant, whose flowers are fertilised by the pollen of another tree (cross-pollination). Flower buds first enter a dormancy phase and usually need a dry period and/or a drastic fall in temperature to enter the flowering process (Figure 5). The necessary time between flowering and maturation of coffee berries depends on the coffee variety but in general are: 6-9 months for *Coffea arabica*, 9-11 months for *Coffea canephora*, 11-12 months for *Coffea excelsa,* and 12-14 months for *Coffea liberica* (Wintgens, 2012). The blooms grow in clusters, are white and smell like jasmine (Feil, 2011).

Figure 5. Sequence of events related to dormancy in coffee tree flower buds



(Source: Wintgens, 2012)

1.3 Ecology

The indigenous Ethiopian species *Coffea arabica* favours a subtropical to temperate climate. This is most prevalent in dry seasons, which should ideally be short and during the cooler period of the year. The dry season should last 6 to 12 weeks, 14 maximum, in order to break the dormancy due to internal water stress. It should not be too long, too hot or too sunny. The hotter period of the year should present mist and/or low cloud, frequently. Concerning atmospheric humidity, Arabica coffee prefers an approximate 60% relative humidity. Rainfalls should be well distributed for all coffee species and a minimum of 1200 to 1500 mm of rain per year is important in order to have good, regular crops. If the rainfall is less abundant, the rain must be well distributed. Excessive rainfall

(> 2500-3000mm) might cause leaching, erosion and make the crop drying difficult. When rainfall occurs during flowering, it can reduce the number of fruit produced. *Coffea arabica* also dislikes frost and strong wind. In general, it is considered that *Coffea arabica* preferably grows between the two tropics. There are some exceptions, however, such as Parana in south Brazil. The *Coffea arabica* tree grows well when the soil is deep, well-drained and loamy. The soil must also be slightly acidic, with high humus and exchangeable base contents, particularly potassium. *Coffea arabica* particularly prefers volcanic soils, which can be found in Colombia and Papua New Guinea (Wrigley, 1988; Descroix and Snoeck, 2012). Table 3 shows the main different typical soils in which coffee is grown but as a general rule, the most suitable soil for coffee plants contains no more than 20-30% of coarse sand (larger than 2mm) and 70% of clay in the upper layers between 30-50cm (Descroix and Snoeck, 2012).

Table 3: Typical coffee-growing soils in the world

Type of soil	***Coffee species planted***	***Geographical areas***
Volcanic ash (sometimes partially laterized)	Arabica	Central America, Colombia, Mexican highlands, Cameroon highlands, Malaysian highlands, Javanese mountain soils (Keloed volcano), Uganda (Mount Elgon)
Soils generated by rocks of a crystalline complex like diorite, gneiss, granite, mica, basalt, megaschist, i.e. arenitas, reddish-yellow podzolic soils, reddisch-brown laterite soils, massapé, terra roxa (purple land), terra vermelha (degraded terra noxa)	Arabica (mostly)	Brazil
Heavy clay soils	Arabica	Andean zone, central Java
Laterite soils	Arabica and Robusta	India, West and Central Africa, Ethiopian plateau, Indonesia (Malang)
Recent volcanic soils (high fertility)	Arabica (mostly)	East Africa, Kivu, Hawaii, Central America
Red and Yellow latosols (acid with a low CEC)	Robusta	The lower lands of the Democratic Repubic of Congo, Ivory Coast
Alluvial soils (high fertility)	Robusta and Arabica	Several limited areas
Kikuyan red loam soils of volcanic origin	Arabica	Kenya
Red sandy clay and gravely loam	Robusta	Uganda

Podzolic soils near the sea	Liberica	Malaysia
Volcanic ash mixed with fragments of lava rocks	Arabica	Hawaii (Kona)
Black humid mountain soils (deep and fertile)	Arabica	Indonesia

(Descroix and Snoeck, 2012)

Coffea canephora and *Coffea liberica* are indigenous to the tropical African rain forests, more precisely the low, hot zones of the Guinea/Congo forests for *Coffea canephora*. Both tolerate heat better than *Coffea canephora* and prefer low altitudes, where the average temperature is around 26°C and rarely goes below 18°C (Wrigley, 1988). Robusta coffee also tolerates the cold better than Arabica coffee, since it can sustain temperature drops of up to 10°C. Concerning rainfall, Robusta coffee needs about 2000 to 2500 mm per year (Descroix and Snoeck, 2012) . According to Wrigley (1988), the most suitable conditions to cultivate Robusta coffee in East Africa include the presence of bananas, elephant grass (*Pennisetum purpureum*) and a lake, which is the case on the northern shore of Lake Victoria from Bukoka (Tanzania) to Kisumu (Kenya). The lake is able to offer a source of rainfall as well as the ability to buffer temperatures. The dry season should not exceed 3-4 months a year, since the evapotranspiration of Robusta coffee plants is higher due to the fact that this coffee species grows in warmer areas. The atmospheric humidity needs to be higher for Robusta coffee than for Arabica coffee, for the latter ranging between 70-75% (Descroix and Snoeck, 2012).

As regards the suitable sunlight and shading conditions for coffee in general, it is important to bear in mind that due to their origin, coffee plants are natural heliophobes. However, in the farming world, it is well known that direct sunlight can increase the intensity of photosynthesis and stimulate flowering, but these benefits require a greater input of fertiliser (Long et al., 2015). Shade is able to regulate the environmental factors of coffee plants, as well as preserve natural resources. Even if the foliage of coffee plants can provide auto-shading which makes additional shading trees redundant, as reported by Descroix and Snoeck (2012), it is important to specify that shade can help to regulate extremely high and low temperatures, in addition to improving the quality of the coffee. The impact of shade will be discussed in more detail in section 4 of the present monograph. To ensure a satisfactory yield, coffee plants should be exposed to sunlight at a rate of 60% during the rainy season and a rate of 60-75% during the dry season. In other words, coffee needs between 2200-2400 hours of sunlight per year (Descroix and Snoeck, 2012).

To obtain more details about the suitable coffee growing conditions for both Arabica and Robusta coffee, the reader may consult **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.**.

1.4 Pests and diseases

This chapter will briefly set out the main pests and diseases that threaten coffee plants globally, along with those which will be assessed in the proposed trials. Moreover, general control methods over these threats to crop health will be given.

1.4.1 Pests

The coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae: Scolytinae) is the most destructive coffee pest worldwide (Rutherford and Phiri, 2006), causing a financial loss of $500 million annually (Vega et al., 2002a). The adult females of this Scolytidae species create holes in mature or immature coffee berries (Picture 1), laying their eggs inside the galleries made in the marketable endosperm. Consequently, larvae feed on this endosperm causing a premature abscission of berries, reduction in weight, yield and quality of berries, as well as making attacked berries more vulnerable to further PDD (Damon, 2000; Rutherford and Phiri, 2006). Both *Coffea arabica* and *Coffea canephora* are affected by this pest, however, Robusta coffee is the most affected. This is because its production of flowers is continuous, and its production zone at a lower altitude is exposed to much higher temperatures and humidity (Damon, 2000). The presence of this pest is easily recognised when one or more small holes can be seen, commonly situated near the apex of the berry (Rutherford and Phiri, 2006).

Picture 1. Hole of *Hypothenemus hampei* in a Robusta coffee cherry, from surveyed field

(Source: Kevin Piato)

Picture 2. Necrosis on a Robusta coffee leaf due to feeding activity of *Leucoptera coffeella* larvae inside leaf, from surveyed field

(Source: Kevin Piato)

The coffee leaf miner (CLM), *Leucoptera coffeella* (Guérin-Méneville) (Lepidoptera: Lyonetiidae) is another important coffee plant pest, especially in Brazil (Souza et al., 1998). Le Pelley (1968), mentioned that this species of moth is present in the neotropical region (South and Central America and most of the islands in the Caribbean). In Brazil, this key pest is responsible for up to 80% of losses in coffee production (Rueda et al., 2016). The CLM larvae damage the leaves by mining which causes a reduction in the photosynthetic surface area (Picture 2), as well as premature defoliation due to an increase of ethylene production. Damage to leaves reduces photosynthetic activity, which in turn results in a decreased cherry yield (Souza et al., 1998). The CLM moth seems to threaten all *Coffea spp*., but it is known that *Coffea arabica* is preferred over *Coffea canephora* (Le Pelley, 1968).

Picture 3. Gallery inside a Robusta coffee stem with *Xylosandrus morigerus* adults, from surveyed field

(Source: Kevin Piato)

The brown twig beetle (BTB), *Xylosandrus morigerus* (Blandford) (Coleoptera: Curculionidae: Scolytinae), is a pan-tropical pest mainly of Robusta coffee plants that grow in warm lowlands. This pest feeds on the fungus *Ambrosiaemyces zeylanicus* Trotter and originated in Asia (Jaramillo et al., 2015). A hole is bored by the female on the underside of the green twig. In this tiny hole with a 1 mm diameter, situated at the core of the twig, the female hollows out a chamber (Picture 3) in which she deposits her eggs (Le Pelley, 1968), causing the necrosis of the inner twig and consequently its death, since the sap can no longer run into the twig. If, however, the twig does not die, the fruit yield is reduced. Besides coffee plants, BTB have other host plants such as the avocado tree (*Persea americana*), the cocoa tree (*Theobroma cacao*) and the pigeon pea plant (*Cajanus cajan*) (Barrera, 2002).

1.4.2 Pest control

Adult female CBB beetles spend most of their life cycle hidden inside the berry and this makes their chemical control very difficult; nonetheless, 2 common insecticides are used, which are endosulfan and chlorpyrifos. Not only do these chemical compounds have side-effects that are harmful for both the environment and humans (Baker et al., 2002;

Weber et al., 2010), but reports from New Caledonia mention resistance to endosulfan (Brun et al., 1989).
To control CBB, another option uses cultivation methods, such as removing dry berries from the coffee plant and/or the floor, and harvesting more frequently. Managing CBB infestation with biological methods is also an option. Both the presence and introduction of natural enemies in coffee fields may impact CBB infestation, as is the case with the entomopathogenic fungus *Beauveria bassiana* (BB) and the wasp parasitoid *Physmatichus coffea*, which comes from Africa (Baker et al., 2002). Above all else, the cultivation method remains the best for small producers because it is safe, simple and accessible. In an ideal world, integrated pest management (IPM) would perhaps be an even more effective method, as it would combine both cultivation and biological methods or more methods if required (Rutherford and Phiri, 2006).

With regard to CLM chemical control, chlorpyrifos, disulfoton, ethion and methyl-parathion are commonly used to control this pest (Fragoso et al., 2002) and, for the moment, they indeed provide the best control (Muller et al., 2012). Systematic use of organophosphates, however, have been reported to cause the development of pest resistance (Fragoso et al., 2002). Although a plethora of Eulophidae and Braconids natural enemies have been recorded in certain coffee plantations (Le Pelley, 1968), their effectiveness in controlling the pests has remained, until now, unknown (Pereira et al., 2007a).

The chemical control of BTB is complicated since the females spend most of their life cycle hidden inside the twig, just like above-mentioned CBB. The use of chemical compounds is only useful when adult females are outside the galleries or during the hollowing out process. In the latter cases, chlorpyrifos and endosulfan are the recommended chemicals (Barrera, 2002), although, in Java, BTB has been reported as having natural parasitic enemies such as the Eulophid, *Tetrastichus xylebororum* and Bethylid. In Le Pelley's opinion, these natural enemies are not able to reduce the population below the economic threshold, even if it is acknowledged that some ants and birds feed upon BTB and fungus BB infects BTB in Ecuador. They are not effective enough and for the time being, control by cultivation techniques remains the best method. More examples of this are : cutting then burning all the infested coffee plants; following an appropriate fertilisation plan; monitoring shade intensity (since excessive humidity favours the fungus *Ambrosiaemyces zeylanicus)* (Barrera, 2002; Jaramillo et al., 2015): all offer a better way of managing this pest.

1.4.3 Diseases

Coffee leaf rust (CLR) is caused by the basidiomycete fungus *Hemileia vastatrix* Berk. & Broome. This coffee disease is potentially the most damaging, since it can cause a 30% crop loss at least and even reach 100% if the attack is severe. This fungus is present in almost all the coffee-producing countries of the world and was the cause of the destruction of coffee plantations in Sri Lanka in the late 19th century (Gaitán et al., 2016). This disease also reduced the level of coffee production in Central America by over 16% between 2011 and 2013 (Avelino et al., 2015).

Coffea arabica is generally the most receptive species to CLR, even though this fungus can affect other resistant species such as *Coffea liberica*, *Coffea excelsa* or *Coffea canephora*. The main symptom is the presence of yellow-orange lesions on the lower surface of the leaves (Picture 4), which cause premature shedding, resulting in a reduction of the plant's photosynthetic capacity and a restricted development of the new stems that will produce cherries the following year. CLR thus has a debilitating effect on the coffee plant over successive years, in addition to accelerating the ripening of the current season's cherries and consequently impairing their quality (Waller et al., 2007). These yellow-orange lesions induce leaf fall and the coffee plants will have different levels of defoliation depending of the intensity of CLR. How severe the attack is, depends on weather conditions, agricultural practices and the species and variety of the coffee.

Picture 4. Yellow-orange lesions of *Hemileia vastatrix* on a coffee branch

(Source: Avelino et al., 2015)

CLR peaks are generally observed in the rainy season in places with an average temperature of 22°C; these conditions are frequently the best for fungal development. Certain growing conditions of coffee crops, such as excess plant density, levels of soil acidity and compaction, weak fertilisation levels, inadequate root development, insufficient weed management, high production levels and yield of cultivars, are all factors which seem to increase the incidence of CLR (Gaitán et al., 2016).

American leaf spot of coffee (ALSC) is reported to be the first disease to threaten American coffee plantations (Gaitán et al., 2016). This disease is only found in America, more specifically in Central and Latin America (CAB International, 1996) and is particularly harmful for coffee plantations in Costa Rica (Avelino et al., 2007). In Central

American coffee plantations, losses of up to 20% or 30% have been estimated (Waller et al., 2007). This disease is caused by the basidiomycete fungus *Mycena citricolor* (Berk. & M. A. Curtis) and can affect around 500 host species in 80 families of plants, including both *Coffea arabica* and *Coffea canephora, as well as* the shade trees used in AFS such as *Erythrina spp.* (ES) (Rivillas and Castro, 2011; Montero, 2015). The asexual conidia are dispersed by wind and rain and germinate in about 1 hour after landing on the plant tissue (Gaitán et al., 2016). The fungus produces spots on the leaves, young stems and fruit. These spots are circular lesions ranging in size between 5-15 mm in diameter and have red borders. The lesions start as brown (almost black) but soon become pale brown and later white or light grey (Picture 5). A very characteristic visual symptom is that the inner part of the spot may fall from the leaf, giving a “shot hole” appearance (Wrigley, 1988; Waller et al., 2007; Gaitán et al., 2016). The main effect of these circular lesions is defoliation, which consequently reduces the photosynthetic area. That disease is known to cause a reduction in growth and production (SENASICA, 2014). Concerning the epidemiology of ALSC, it seems that it is most prevalent in heavily shaded and high-rainfall locations (Waller et al., 2007; Wrigley, 1988; Rivillas and Castro, 2011; SENASICA, 2014), whereas under sunny planting conditions the disease seems to be completely absent (Gaitán et al., 2016). ALSC develops mainly in coffee plantations between 1100 masl and 1550 masl, in areas with a cool temperature (Avelino et al., 2007).

Picture 5. Leaf lesions caused by *Mycena citricolor*

(Source: SENASICA 2014)

Picture 6. Spots of *Cercospora coffeicola* on Robusta coffee leaves, from surveyed field

(Source: Kevin Piato)

Cercospora leaf spot (CLS) is a major coffee plant disease that can reduce harvest values to less than 30% (Gaitán et al., 2016). CLS has a worldwide distribution and is caused by the fungus *Cercospora* *coffeicola* Berk. & Cooke, the imperfect stage of the ascomycete *Mycosphaerella coffeicola* (Cooke). It can infect most species of coffee (Waller et al., 2007), although Arabica coffee seems to be the most vulnerable (Muller et al., 2012). The CLS symptoms first to be observed, are the developing of small, brown, chlorotic or necrotic spots, ranging up to 15 mm in diameter on either surface of the leaves (Wrigley, 1988). Then the inner part of the lesions can become noticeably greyish and are surrounded by a brown ring, and sometimes with a diffuse external chlorotic halo (Picture 6, Gaitán et al., 2016a). The "eye spot" appearance of the infected leaves distinguish CLS from other leaf spots such as ALSC (Wrigley, 1988).

Later the disease spreads to the green and ripe fruit where small reddish lesions begin to appear, particularly when the fruit is protected from direct sunlight. Infected green fruit can then become prematurely ripe and thus drop from the branch. Berries suffering from mature lesions are brown with a red ring and eventually begin to look dry and dark brown in colour. The skin and pulp of these berries can stick to the beans which may mean that the berries are not pulped correctly before the fermentation process (Gaitán et al., 2016).

Unlike ALSC, CLS is more abundant in unshaded coffee plantations, where the period of fungus incubation is shorter than in plantations not exposed to sunlight. Alongside these conditions, the levels of nitrogren nutrition and the high temperature and humidity can play a part in the prosperity of CLS (Wrigley, 1988; Gaitán et al., 2016).

The fungus which causes CLS consists of conidia and ascospores which are easily dispersed by wind and rain. Therefore, in shaded plantations, the sheer weight of the water falling from the leaves above the coffee plants could increase the rate of dispersion of these spores.

Thread blight (TB) is an important disease affecting many plants, including both *Coffea arabica* and *Coffea canephora* It can cause crop losses of up to 10%-20% in coffee plantations and 70%-80% in individually affected coffee plants (Gaitán et al., 2016). Interestingly, Robusta coffee is reported to be more susceptible to the disease than Arabica coffee (Waller et al., 2007).

Picture 7. Dead brown Robusta coffee leaves infected by *Pellicularia koleroga* remaining attached to the branch by threads of the fungus, from surveyed field

(Source: Kevin Piato)

TB is found throughout coffee plantations in Latin America and the Caribbean but it is particularly widespread in India. It has also been recorded in South-East Asia, some of the Pacific Islands and in parts of Africa (Waller et al., 2007). In Ecuador, TB is caused by fungus *Pellicularia koleroga* Cooke, which threatens the coffee-growing areas of all parts of the country and has a huge economic importance.

Symptoms consist of white thread-like mycelium growths on the underside of leaves, on cherries and twigs (Sotomayor, 1993). Later this coating becomes brown and the leaves become yellow before they die and turn black in colour (Picture 7). The dead leaves remain attached to the branch by the mycelium of the fungus. This last symptom is a key characteristic of the fungal infection (Jackson, 2017).

During the dry season, the fungus survives through the sclerotia which remains on the dead host leaves. The infected fruit then dries and finally falls from the branch. The conditions that favour the development of TB are: excessive shade, high plantation density, high humidity, and cool, wet weather. For this reason, this disease may be more common at higher altitudes (Waller et al., 2007). The fungus is mainly active during the rainy or monsoon season (Sotomayor, 1993).

Another very important disease to note is coffee berry disease (CBD). It is such a significant threat to Arabica coffee plantations confined to the African continent that it cannot go without mention (Bedimo et al., 2010; Muller et al., 2012; Gaitán et al., 2016). Crop losses in Arabica coffee plantations can reach 20-30% in Africa and even exceed 80% in extremely wet years (Gaitán et al., 2016). Damage can be dramatic, since the disease can destroy the berries directly. To date, the disease affects only Arabica coffee plants (Wrigley, 1988) and is caused by the Ascomycetes fungus *Colletotrichum kahawae* J. M. Waller & Bridge. Even though CBS can affect the berries at every stage of development, a clear diagnosis can only be made on young green fruit. The main features of the disease are active anthracnose and scab lesions. Scab lesions are slightly concave pale spots and active lesions of CBS are darker and are much more concave, which can result in the entire berry being covered by the lesion (Picture 8). Scab lesions are also covered by a few black specks called

Picture 8. Coffee berries infected with *Colletotrichum kahawae*

(Source: Cirad)

acervuli. Active lesions are more commonly found on young berries, whereas scab lesions are found on more mature berries, since the latter are more resistant to CBS (Muller et al., 2012). Concerning the epidemiology, water conditions play a key role in spore production, dispersal, germination and the infection process (Gaitán et al., 2016).

In the present study, the incidence and severity *of Colletotrichum spp*. (CS) have been assessed on Robusta coffee. Because of the dark shaped foliar lesions observed in Picture 9, this may be the fungus *Colletotrichum gloeosporioides* or a mixture of species including *Colletotrichum gloeosporioides* (Gautam, 2014).

Picture 9. Leaf lesions caused by *Colletotrichum spp.* observed on Robusta coffee plants in surveyed field

(Source: Kevin Piato)

Another important disease which has been evaluated in the present study is the dieback caused by the Deuteromycetes fungus *Phoma spp*. (PS). This important fungus can cause crop losses up to 80%, as previously observed in Guatemala (Franco, 2013). As mentioned by Franco (2013), the disease is more common on Arabica coffee as the fungus grows better above 1600 masl, although it has been reported in Mexico below 900 masl. Indeed, the fungus thrives in extended rainy periods, low solar radiation, low temperatures (between 18°C-22°C) and cold winds. The first symptoms appear 4-9 days after infection. The main features of the disease are small, irregular, chlorotic spots on meristematic buds and leaves which lead to necrosis after 10 days, as observed in Picture 10.

Picture 10. Necrotic spots on leaves caused by *Phoma spp.* on Robusta coffee plants observed in surveyed field

(Source: Kevin Piato)

1.4.4 Disease control

Controlling CLR by chemical means can be done by applying protective copper-based fungicides at regular intervals. Foliar systemic fungicides such as those from the azole group (e.g. cyproconazole, triadimefon, hexaconazole and flutriafol) and strobilurins (e.g. azoxystrobin and pyraclostrobin) provide effective disease control (Muller et al., 2012; Gaitán et al., 2016). Treatments should begin at the first sign of rainfall (before the initial CLR attacks) and be pursued for as long as the pathogen is active (Muller et al., 2012).

Genetic control has been, and is still, widely researched, seeking to obtain complete CLR-resistant hybrids. To date, the most used hybrid that has been found is named 'Timor Hybrid'; it is tetraploid, self-fertile and spontaneous, a hybrid between *Coffea arabica* L. and *Coffea canephora* Pierre ex A. Froehner. The Centro de Investigaçao das Ferrugens do Cafeeiro (CIFC) in Portugal has already identified 9 resistance genes (SH1 to SH9). The genes SH6 to SH9 are found in 'Timor Hybrid', issuing from *C. canephora*. The use of certain accessions of 'Timor Hybrid' of the CIFC has resulted in new varieties e.g. 'Catimor' and 'Colombia' (Muller et al., 2012; Gaitán et al., 2016). The aforementioned varieties are widely used in coffee plantations but seem to suffer from rapid plant exhaustion, notable physiological failures, in addition to a decreasing cup quality (as is the case for 'Catimor'). All the genes from these varieties show vertical resistance and, at the moment, research is being carried out to associate this specific resistance with horizontal resistance. This combined resistance could reduce the intensity of the onslaught of the disease, especially in cases where there is a loss of resistance. This research could lead to a large improvement of the cup quality. On the other hand, general resistance alone can be found in wild genotypes of Arabica coffee in Ethiopia (Muller et al., 2012) and more details about this type of resistance with respect to coffee breeding will be given in the following section.

Managing ALSC in coffee plantations relies mainly on cultivation techniques that improve soil structure by reducing its humidity (Rivillas and Castro, 2011; Wrigley, 1988). This is achieved by pruning coffee plants and shading trees, thus regulating the relative humidity inside the plantations (SENASICA, 2014); by using less sensitive coffee varieties, such as 'Catuaí' and 'Caturra' (Montero, 2015); by immediately removing all the infected coffee parts discovered; and by maintaining the coffee plants in a good nutrition state (Rivillas and Castro, 2011). Avelino et al. (2007) found, however, that when determining epidemic risk, the altitude, aspect and inclination of the slopes are far more significant factors than the density of shade itself.

The biological control agent *Trichoderma harzianum* (Tricho-D®) can be effective in monitoring ALSC. If required, copper-based fungicides (e.g. copper oxychloride, cuprous oxide, and a Bordeaux mixture) can be applied to prevent infections and in case of attack, systemic chemicals based on cyproconazole or triadimefon provide effective control (Wrigley, 1988; Gaitán et al., 2016).

The management of CLS in coffee plantations, similarly to ALSC, is mainly based on cultivation techniques by avoiding excessive sunlight and applying appropriate fertilisation that will prevent nutrient deficiency and over-fertilisation. Under nursery conditions, all the factors that affect the coffee plant's health must be checked. This is done by using a certified seed and large nursery bags, by transplanting the seedlings into substrates with organic matter (e.g. coffee pulp compost) as well as adding nitrogen and phosphorus fertilisers. In cases of CLS outbreaks, chemical control may be required. In a coffee nursery, this would call for carbamate fungicides and in a plantation, a mixture of copper oxychloride, triazole and vegetable oil would be used within the 90-120 days following the main flowering event (Sotomayor, 1993; Gaitán et al., 2016).

TB is mainly controlled through cultivation techniques. Firstly, the shade regulation will provide sufficient air and light throughout the plantation. Secondly, removing all the infected parts will reduce the need for inoculum and occurrence of the disease in the following season. These actions should be performed during the dry season and all the removed plant parts must be burned outside the coffee-growing area. A chemical treatment can be copper-based and used before the rainy season and if not sufficient, a 50% carbendazim wet table powder can be applied in dry weather conditions (Sotomayor, 1993; Gaitán et al., 2016).

Managing CBD relies mainly on cultivation practices which reduce the conditions favouring fungal development and include pruning to prevent crop cycles from overlapping. The use of chemical compounds is not recommended since they may destroy indigenous fungal antagonists, but it is extremely common. Consequently, using fungicides against CBD has been reported as increasing the occurrence of *Pellicularia koleroga*, whereas fungi such as *Fusarium stilboides* (Wollenw.) and *Epicoccum nigrum* (Link) have been reported as playing a notable role in the mitigation of CBD. In the field of moderating fungal disease, the use of resistant varieties of *Coffea arabica* is also promising. The variety 'Rume Sudan' and the interspecific tetraploid hybrid 'Timor Hybrid' have been identified as having high resistance to fungus and because of this, they are included in the breeding programmes of African countries to create new resistant varieties (Catimor 128, Catimor 129 and Ruiru 11). Similarly, Caturra and Catuai varieties are not advocated but are still used because they are very susceptible to CBD (Gaitán et al., 2016).

PS is mainly controlled by producing healthy coffee seedlings in the nursery and using coffee plants without symptoms. As infected leaves and/or buds appear, they must be removed and all the coffee plants treated with a proper fungicide. Before the rainy season, it is advisable to treat the plants with a fungicide and to continue the applications monthly. It is also recommended to apply windbreaking techniques, such as intercropping the coffee plants with banana plants, corn or shelter trees, in order to limit spore dispersion. The fungicides which can be used are: dichlofluanid, captan, cyproconazole, anilazine and iminoctadine (Gaitán et al., 2016).

1.5 Coffee breeding

Coffee plants have been bred since the 17th century (Bertrand et al., 1999). For both Arabica and Robusta coffee, the general objective of coffee breeding programmes is to develop new cultivars which provide better economic returns for the growers (Vossen, 2001). As shown in Table 4, the selection criteria applied to coffee breeding indicates the equal importance of productivity in both aforementioned species, but the higher priority of quality (bean size and shape, and quality of liquor) and host resistance to diseases, especially to CLR and CBD in Arabica coffee.

Table 4: Selection criteria applied to coffee breeding

Criteria	Priorities	
	Arabica	Robusta
Productivity		
Yield: kg per plant and per hectare	3	3
Yield stability	3	3
Plant vigour	3	3
Compact plant type (short internodes)	3	2
Quality		
Bean size and shape	3	1
Liquor quality	3	2
Caffeine content	1	2
Host resistance to diseases		
Coffee leaf rust	3	1
Coffee berry disease (Africa only)	3	—
Other diseases	1	1
Host resistance to pests		
Nematodes	3	1
Leaf miners	2	1
Coffee berry borer	2	2
Stem borers	2	1
Drought tolerance	1	1

Note: 1 = low, 3 = high breeding priority.

(Vossen, 2001)

The yield of a coffee plantation is highly dependent on the environment, as is the case for *Coffea arabica,* and this adds a few difficulties to coffee breeding. Indeed, 23-56% of the total variation in yield have been attributed to environmental factors (Medina et al.,

Table 5: Summary of main coffee breeding methods

Method	Source populations	Breeding system	Output	Popagation by	Examples
Arabica					
(1) Pure line selection	Variety	Selfing	Line	Seed	Caturra (Brazil), Kents (India) SL28 (Kenya), Java (Cameroon)
(2) Pedigree selection after hybridization (sometimes also backgrossing)	Varieties	Crossing and selfing	Line	Seed	Catuai, Tupi (Brazil), Catimor Sarchimor (Costa Rica), S795 (India) Colombia (Colombia)
(3) Intraspecific F1 hybrids	Varieties/ accessions, pedigrees of crosses	Crossing and selfing	Composite hybrid F1 hybrid F1 clone	Seed (hand pollination) som. embryogenesis	Ruiru II (Kenya) Ababuna (Ethiopia) in progress: Catimor × Et (C. America)
(4) Interspecific hybridization (arabica × robusta), backgrossing and pedigree selection	Arabica varieties, tetraploid/diploid robusta genotypes	Crossing and selfing	Line	Seed	Icatu (Brazil), S2828 (India)
Robusta					
(5) Mass selection (individual plants)	Local or introduced varieties and accessions	OP (open pollination)	OP variety	Seed	Apoata (Brazil), S274 (India) Nemaya (C. America)
(6) Family and clonal selection	Varieties, clones	OP (half-sib families)	Synthetic variety (bi-, polyclonal gardens) clone	Seed	BR sel 2 (India), SA and BP selections (Indonesia) IF 126, 202, 461 clones (Ivory Coast) BP39, BP42 (Indonesia)
(7) Reciprocal recurrent selection	Varieties, clones (distinction of two sub-populations)	Bi-parental crossing for inter-group combining ability tests and intra-group recombination; + doubled heploids	Synthetic hybrids (bi-clonal gardens) clone F1 hybrid	Seed Cuttings or somatic embryogenesis Seed	In progress (Ivory Coast, France) In progress (Ivory Coast, France)
(8a) Interspecific hybridization (arabica × robusta), family and clonal selection	Arabica variety, tertaploid robusta genotypes	Crossing and OP	Synthetic hybrids (poly-clonal gardens) clone	Seed Cuttings	Arabusta (Ivory Coast)
(8b) Interspecific hybridization (*C. congensis* × robusta), backcrossing to robusta and family selection	*C. congensis* accession, robusta genotypes	Crossing, backcrossing, sib-mating	OP variety	Seed	C × variety (India)

(Vossen, 2001)

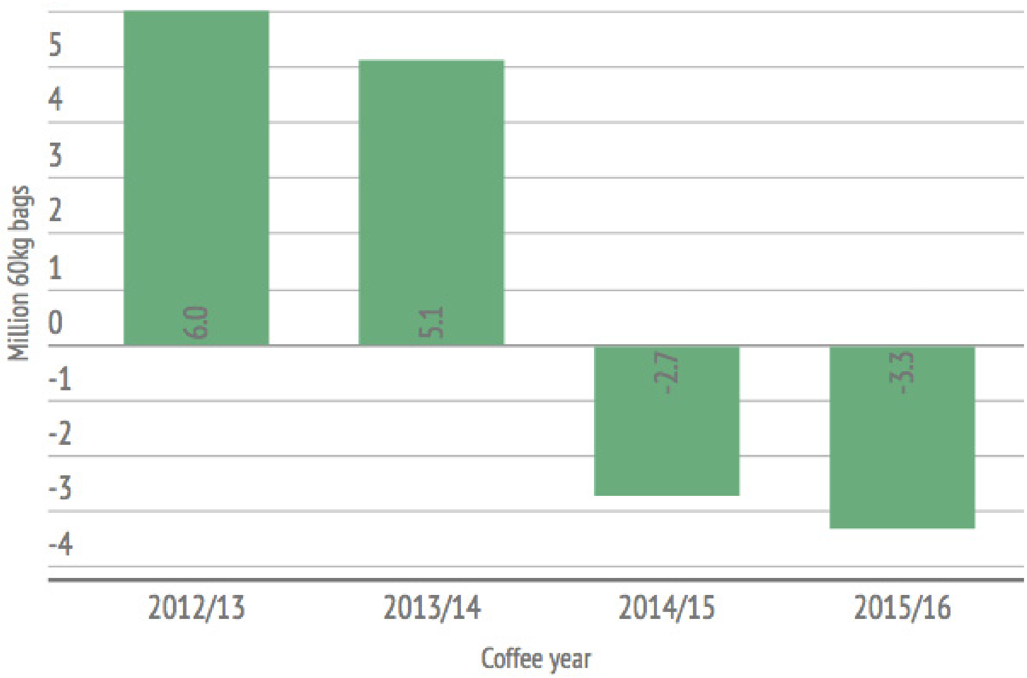
1984). Another major hindrance when developing new coffee varieties is the time and resources needed, since new cultivars take about 25 years to develop. The process of coffee breeding starts with seeds that take quite a long time to generate coffee (5-6 years), in addition to the fact that coffee plants and therefore crops are perennial (Moncada et al., 2016). The main breeding methods for both Arabica and Robusta coffee are summarised in Table 5. For more detailed information about the coffee breeding scheme, the reader may consult **Erreur ! Source du renvoi introuvable.**. Traditionally, to improve autogamous Arabica coffee, pure lines are selected, while improving Robusta coffee requires selection of clones and hybrids between clones (Eskes and Leroy, 2012; Déchamp et al., 2015).

Recent developments in coffee breeding aim to shorten the time needed to create a new variety by using marker-assisted selection (MAS). To improve MAS it is necessary to identify markers associated with quantitative trait loci (QTLs) which govern interest traits. To that aim, it is necessary to perform genetic mapping (Zamarripa and Pétiard, 2012; Moncada et al., 2016) as shown for Robusta coffee in **Erreur ! Source du renvoi introuvable.**. Another current trend of coffee breeding research is to develop and assess new hybrids which are generally created by crossing a wild coffee species and a cultivated coffee species (Bertrand et al., 2011; Ogutu et al., 2016).

2. Global economic facts

Besides water, coffee is the most popular beverage in the world with more than 400 billion cups consumed every year (Illy, 2002). The main coffee varieties produced and traded in the world are *Coffea arabica* and *Coffea canephora*, which respectively represent 65% and 35% of the entire worldwide coffee production (ICO, 2016). Furthermore, the consumption of coffee is steadily increasing, the average annual growth rate of global coffee consumption since coffee year 2012-13 being 1.3%. The estimated number of 60-kg bags of coffee consumed and produced in coffee year 2015-16 (Oct. 2015 to Sep. 2016) is respectively 151.3 million and 148 million. As these figures show

Figure 6. Estimated deficit between coffee production and coffee consumption in the world in 2015-2016



(Source: ICO, 2016)

and since 2014-2015, global annual coffee production does not meet the demand of global annual consumption. In Figure 6, we see that estimated deficit between production and consumption in 2015-16 is 3.3 million 60-kg bags but the stocks accumulated in 2012-2013 and 2013-2014 are sufficient to well supply the market. Despite this deficit, the total production from all exporting countries has increased globally: rising from 93.1 million 60-kg bags in 1990-1991 to 153.87 million 60-kg bags in 2016-2017. The three main coffee producing export countries are Brazil, Vietnam and Colombia with a respective total coffee production in 2016-2017 of 55, 25.5 and 14.5 million of 60-kg bags (ICO, 2016).

The coffee prices paid to growers in exporting countries averaged 50 US cents/lb in 1990 and 103.61 US cents/lb in 2016. According to the most recent available data for 2016, this coffee price was lowest in Central African Republic with 30.74 US cents/lb and highest in Bolivia with 271.79 US cents/lb. A similar upward trend is shown by retail prices of roasted coffee in importing countries with an average price of 4.53 US$/lb in 1990 and 5.85 US$/lb in 2016. The most recent ICO data (International Coffee Organization) for year 2016 revealed that this retail price was lowest in Poland with 3.17 US$/lb and highest in The United Kingdom with 16.29 US$/lb (ICO, 2016).

With a global retail value of US$70 billion (in 2003), coffee is the most traded commodity apart from oil. The socio-economic impact of coffee production is huge, due to the fact that the coffee market provides a livelihood for more than 100 million people in the world, mostly coffee producers (Vega et al., 2003). About 70% of the coffee plantations are small-scale farms, smaller than 10 ha. On a broader, international scale the coffee trade involves about 500 million people from cultivation to consumption (DaMatta et al., 2007). With coffee price volatility, this dependence can cause dramatic social and economic impacts. Indeed, between 2000 and 2002, coffee prices paid to growers suddenly dropped, drastically. This is due to an overproduction by nearly 53% in Brazil and Ethiopia, 30% in Colombia and 32% in Vietnam (ICO, 2016). Among other consequences, 540000 coffee workers have lost their jobs in Central America because of these price decreases (Vega et al., 2003).

3. Coffee cultivation

3.1 Global challenges

There is a widespread belief that unshaded coffee plantations can yield more than those which are shaded. Thus, in some countries, sun-exposed plantations have been promoted at the expense of the traditional shaded coffee growing plantations (Beer et al., 1997; Jonsson et al., 2015). Certain farmers have managed to triple, or even quadruple, their yield by replacing a buffered shaded environment with petroleum-based pesticides and fertilisers, thus shortcutting the ecological cycles (Haggar et al., 2011).

Consequently, full sun-exposed coffee plantations depend on chemical input, incurring high costs. This is not readily accessible to small-scale family coffee farmers who represent the majority of coffee producers (Jaramillo et al., 2013). This difficulty, coupled with the high variability of coffee prices on international markets (Vega et al., 2002b), means that intensive coffee monocultures with little or no shade environments are not sustainable.

Another global challenge is related to climatic evolution, as the coffee plant is highly sensitive to climate change (Bunn et al., 2015). The IPCC (Intergovernmental Panel on Climate Change) predicts a desertification rate of Latin American agricultural lands of about 50% by 2050, as a consequence of rapid global warming (IPCC, 2007). Because coffee breeding takes decades, global coffee production is threatened and, above all, the livelihood of over 100 million people (Eskes and Leroy, 2012). It has been scientifically proven that *Coffea arabica* is more sensitive to heat than *Coffea canephora*, but the problem is that the climate will present more intra-seasonal variations in temperature, in addition to an overall temperature rise. As *Coffea canephora* is more sensitive to temperature variations and *Coffea arabica* is more sensitive to warmer temperature, both species could be equally affected by global climate change. The future Arabica coffee-growing areas that will be impacted the least are in Eastern Africa currently non-forested, unlike the forested areas in Asia and other parts of the world. Policy-makers must therefore control deforestation in Asian areas, and coffee AFS must be promoted in African coffee cultivation areas (Bunn et al., 2015).

3.2 Challenges in Ecuador

A great strength of Ecuador is the ability to produce both Arabica and Robusta coffee. For 20 years, Ecuadorian coffee crop production has been decreasing, with 1504 thousand 60-kg bags produced in 1990-1991 and 645 thousand 60-kg bags produced in 2016-2017. The same trend is shown by domestic consumption with 350 thousand 60-kg bags in 1990-1991 and 155 thousand 60-kg bags in 2016-2017 (ICO, 2016). The total coffee area harvested in 2017 was 37 260ha and the total production of green coffee was 7564 t (ESPAC, 2017). The aforementioned drop in coffee production is due, according to the Ecuadorian Government, to ageing coffee plantations which cause a decrease in production. Other reasons are the lack of agronomical knowledge of coffee growers, the fact that some coffee fields are situated in border regions, the lack of financial resources to renew infrastructure and the lack of knowledge in coffee post-harvest processing. Considering the social, economic and ecological importance of Ecuadorian coffee plantations, the Government has created the national project "Proyecto de Reactivación de la Caficultura Ecuatoriana" whose objectives are to promote the productivity, the return, the research, coffee quality improvement and the institutionalisation of the coffee value chain. Currently, the second phase of this national project is being carried out, running until 2020 (MAGAP, 2017).

Ecuadorian coffee is economically important, since it represents about 3% of the national agricultural GDP, 80% of coffee plantations have a size of less than 5ha, 13% between 5ha and 10ha and 7% more than 10ha. Land ownership is a great problem in Ecuador, since 20% of the coffee areas are not legalised by land ownership. 105 000 families are involved in coffee production in Ecuador (MAGAP, 2017).

3.3 Challenges in the Ecuadorian Amazon

The EAR is responsible for 67% of the national Robusta coffee production. Not only do 62.4% of the farms in this region cultivate coffee but two specific provinces are responsible for 88% of the entire Robusta output of this region: Orellana and Sucumbíos. Agriculture in the EAR is nonetheless limited mainly due to unsuitable soil characteristics, structural problems (Subía et al., 2014), pests and disease impacts and the lack of education and training for farmers (Nieto and Caicedo, 2012). One of the possible solutions in this agricultural crisis is AFS which, as discussed below, could improve the livelihood of the farmers as well as help to preserve the environment (Subía et al., 2014).

3.4 The INIAP experiment on *Coffea canephora* in the Ecuadorian Amazon

Within the context described in the previous section, the Estación Experimental Central de la Amazonía (EECA), a part of the INIAP, have deemed it necessary to perform a medium- and long-term trial. This would allow different Robusta coffee growing systems to be assessed in an interdisciplinary and integrative manner. By performing this trial, the EECA seeks to measure the interaction between the growing systems for Robusta coffee and its cultivation, so as to provide tools in the medium and long term that will promote mechanisms for change in traditional Robusta coffee growing systems. The improvement of traditional coffee growing systems must be achieved within a sustainable development perspective and requires the assistance of coffee growers.

The general objective of the EECA's experiment is to assess Robusta coffee AFS by varying the farming practice in Joya de los Sachas. The specific objectives of this governmental trial are:

- To assess the effects of shading and different farming techniques on Robusta coffee PDD,
- To assess the effects of shading and different farming techniques on biological, chemical and physical soil characteristics,
- To assess the agronomic behaviour of *Inga edulis* (IE) as a constituent of Robusta coffee AFS,
- To assess the agronomic behaviour of forest species (*Myroxylon balsamum* (L.) (MB) and ES), as constituents of AFS in Robusta coffee plantations,
- To estimate the carbon content stored in the aerial biomass of Robusta coffee AFS at 4 different moments,
- To assess yield capacity and susceptibility to pests and diseases of 9 promising genetic materials of Robusta coffee in AFS,
- To assess the chemical quality of Robusta coffee mucilage in 2 different AFS,
- To analyse the economic return of Robusta coffee in AFS by varying the farming practice.

4. Coffee agroforestry systems

4.1 Functions

There are many definitions of agroforestry but the recurring concept is a farming practice associating crops with trees (Jonsson et al., 2015; Meylan et al., 2017) and/or animals with trees and/or animals and crops with trees in the agro-ecosystem, in order to obtain products or useful services (Torquebiau, 2000). Torquebiau, however, adds to his definition that agroforestry is merely one of the many agricultural techniques used to increase output. He discusses how different circumstances require varying techniques aside from the use of agroforestry (Torquebiau, 2000).

The functions of AFS in terms of the benefit yielded for the coffee agro-ecosystem are controversial. On the one hand, some publications affirm that AFS bring benefits as a climate buffer notably improving temperature, humidity and wind speed parameters; as conserving and improving natural resources and biodiversity (Boreux et al., 2016; DaMatta, 2004; Tscharntke et al., 2011), as well as soil fertility, mainly in the way of reducing erosion and thus N-losses (Beer et al., 1997; Tully et al., 2012); as increasing infiltration rate of water in the soil because of bigger litter deposit in AFS (Meylan et al., 2017). AFS also reduce any overbearing (Beer et al., 1997; DaMatta, 2004) in the limitation of light transmission, and also reduce nutritional imbalances and dieback (Beer et al., 1997). AFS can also homogenise coffee crop production which reduces bienniality. This has been observed in full-sun coffee plantations (DaMatta, 2004). It also gives a more stable income because shelter trees can provide additional revenue by producing fruit and timber (DaMatta, 2004). This additional revenue can even represent 11-49% of the net present value (NPV) (Sousa et al., 2016). The use of N-fixing trees such as Erythrina (Meylan et al., 2017) in AFS allows reduced input or compensates low-input farming management (Nygren et al., 2012). According to the recent study of Alves et al., 2016, AFS can improve the vulnerable economic situation of coffee growers, particularly in the Brazilian Amazon, since coffee production costs in coffee AFS are lower than those in full sunlight coffee plantations. Indeed, better coffee net margins are obtained with coffee AFS as shown in Table 6, since coffee fields under full sunlight have a less homogenous productivity than those under shade and they need more weed suppression time (Alves et al., 2016).

Table 6: Net margin in various shaded and full sun Robusta coffee plantations

Agrecossytem	Pruning and thinning	Mowing	Harvesting	Drying	Total cost of production	Net Margin
Shaded						
I	6.20%	16.30%	28.50%	4,13%	55.13%	44.87%
II	20.00%	4.8%	30%	00	54.80%	45.20%
III	00	17.11%	26%	2.97%	46.08%	53.86%
IV	4.56%	4.0%	30%	6.84%	45.4%	54.6%
Full Sun						
V	29.10%	25.60%	30%	3.60%	88.30%	11.70%
VI	25%	33.10%	30%	6.5%	94.60%	5.40%
VII	29.41%	12.65%	29.41%	6.98%	78.45%	21.55%
VIII	26.31$	9.56%	26.31%	5.27%	67.45%	32.55%

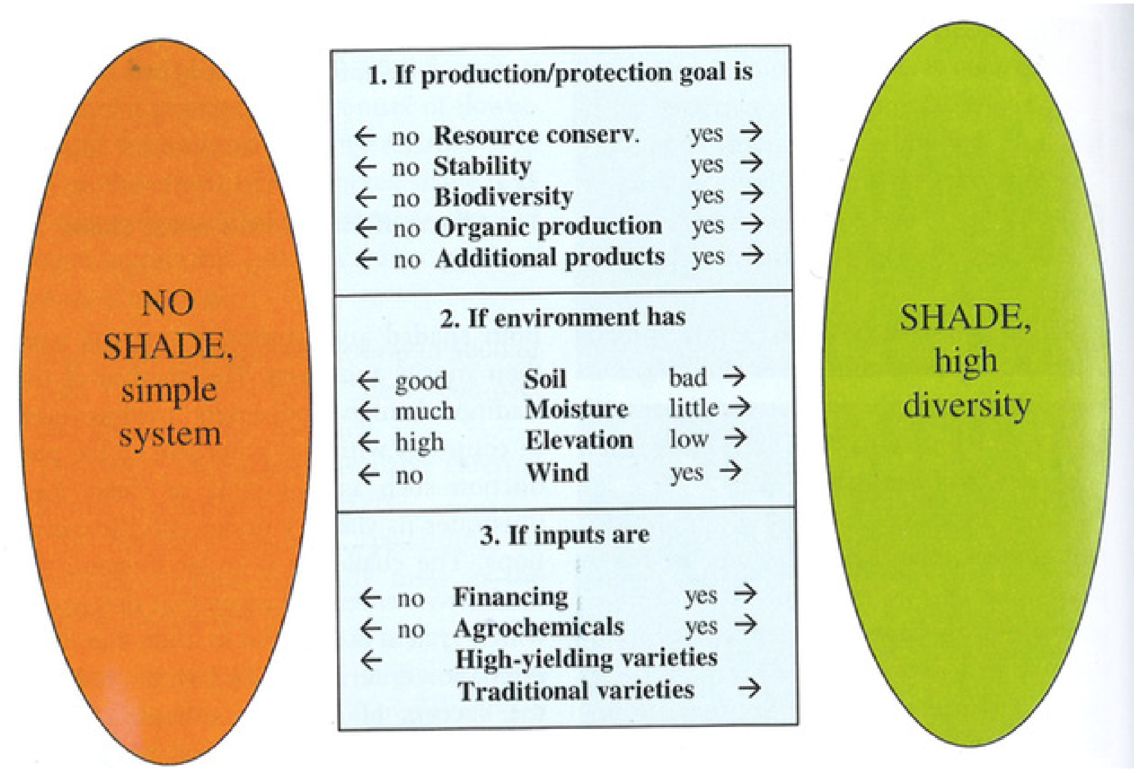
(Alves et al., 2016)

Furthermore, Vaast et al. (2006) demonstrated that shade can provide a better beverage quality for Arabica coffee in Costa Rica by delaying the period of ripening by up to 1 month. However, this effect of shading has been shown, in Colombia, to depend on the altitude of the crop (Bosselmann et al., 2009). Finally, AFS can play a positive role in reducing the volume of weeds, pests and diseases in coffee plantations (Pumariño et al., 2015), as well as contributing to the overall increase of the berry yield in some specific systems (Boreux et al., 2016).

On the other hand, some negative aspects of AFS are reported in scientific litterature. The most common drawback reported is competition for water and nutrients between crops and trees, especially in cases of excessive shade (Beer et al., 1997; Noordwijk et al., 2015), as well as decreases in yield for Arabica coffee (Campanha et al., 2004). Regarding biodiversity, Smith (2015) even concludes that in Kenya, bird communities are more numerous and diverse in sun plantations than in shaded ones.

How can these contradictions be explained? It is possible that there is a trade-off between the positive impacts of AFS against the negative? For example, shading can decrease the volume of weed but increase the risk of CLR (Silva and Tisdell, 1990). The effectiveness of AFS could depend on site conditions such as altitude (Beer et al., 1997; Cerda et al., 2017), climate parameters (Campanha et al., 2004; Noordwijk et al., 2015), and the type of trees used (Boreux et al., 2016; Haggar et al., 2011). The type of crop could also be a factor of effectiveness as reported by Nesper et al. (2017), who suggested that the shading impact on coffee production can differ between *Coffea canephora* and *Coffea arabica*. The effectiveness of the type of crop could also vary with the type of farming practice, particularly the pruning of trees (Haggar et al., 2011; Schnabel et al., 2017). According to Schnabel et al. (2017), it is very important to thin timber trees in order to maintain an adequate shade level in AFS. The type and amount of shade could also play an important role in the success of AFS (Estívariz and Muschler, 1998), as well as the type of crop management (Cerda et al., 2017). Thus, to evaluate the usefulness of AFS in terms of benefits for the farmer, requires taking into account biophysical, socio-economic and policy parameters (Cannell et al., 1996). Muschler (2012) has proposed a decision tree to help making a decide about growing coffee with or without shade (Figure 7). This decision tree includes 3 groups of objectives, namely the protection goals, the environmental conditions on the particular site and the availability of inputs (Muschler, 2012). The weakness of this tree is that in the final decision, it does not propose a gradient of shade quantity, but only the presence or absence of shade. The positive point of this approach, however, is that it offers a simple orientation to the coffee grower.

Figure 7. Decision tree which helps the coffee grower decide whether to grow coffee under shade or not



(Source: Muschler, 2012)

4.2 Shading effects on the development of coffee pests and diseases

The impact of shade on PDD is also an ambiguous topic because the impact may vary with the type of crop, the pest, the disease, the microclimate or, in particular, when it is associated with a perennial crop (e.g. coffee, cocoa and plantain). No notable effect on pest abundance is observed when it is associated with annual crops (e.g. maize, rice and beans). A common assumption is that AFS provide better pest regulation than crop monocultures (Jonsson et al., 2015), because they can host greater biodiversity and more complex food webs (Vandermeer et al., 2010), in addition to increasing the number of natural enemies (Pumariño et al., 2015). Another reason on which this assumption is built is the fact that crops in a multicultural context are less damaged by pests than the crops as monocultures (Letourneau et al., 2011), the reason being that pests have greater difficulty in finding their host plants and/or remaining on them, since AFS offer a more suitable microclimate for natural enemies (Root, 1973). As these outcomes are not universal (Jonsson et al., 2015), the varying impact of AFS in the context of pest and disease regulation will be discussed in the following sections. This variation could be explained by the fact that AFS could reduce the damage due to pests and diseases but not necessarily their abundance (Pumariño et al., 2015). The shading effects on PDD will be addressed separately for each Arabica coffee and Robusta because, as mentioned above, these 2 varieties do not have the same ecology (Davis et al., 2006) and the same type of fertilisation characteristics (Ferwerda, 1948), which could cause fluctuations in shading effects (Beer et al., 1997; Cerda et al., 2017; Nesper et al., 2017). Furthermore, *Coffea arabica* and *Coffea canephora* may not have the same sensitivity to pests and diseases (Mariño et al., 2017).

4.2.1 *Coffea arabica*

One of the most predominant effects relates to CBB infestation. Atallah et al. (2018) calculated that the optimal shading level in Colombia in the presence of CBB infestation is 25%. With this level, AFS could be more profitable for the farmer than full-sun coffee systems (Atallah et al., 2018). This means that shade could reduce the CBB infestation rate on coffee plants. CBB infestation can increase in sun-grown Arabica coffee plantations because of the higher average and maximum temperatures (Jaramillo et al., 2013). Jonsson et al. (2015) also found that CBB is less common in shaded plantations than in those which are sun-exposed. Where CBB infestation is concerned, all these publications demonstrate the positive impact of shading on Arabica coffee. This is important in a context where climate is changing, in that it would enhance CBB damage on coffee plantations (Jaramillo et al., 2009). Many mechanisms have been proposed in order to explain this negative effect of AFS on CBB infestation. Tree shading could be an effective approach to manage CBB infestations because ants, birds, hymenopterans like *Azteca instabilis* and the entomopathogenic action of BB could benefit from shelter trees (Baker et al., 2002; Staver et al., 2001; Karp et al., 2013; Mariño et al., 2016). This would enhance the biological control of CBB in coffee shaded plantations because these organisms would thrive in this shaded environment.

Karp et al. (2013) found that the use of shade can diminish the rate of CBB infestation by up to 50%, however, changes in temperature may also contribute to reducing this pest infestation, as reported by Jaramillo et al. (2009). The reason for this is that CBB is much less active when the average daily temperature is lower and thus the number of these pests declines. The same publication reported that average daily temperatures in the last three decades in Ethiopia ranged between 17.3°C and 22.3°C and in Tanzania between 22.3°C and 29.8°C, as well as noting that the potential number of generation of CBB was between 1.3 and 3.1 per year. These observations support the association between temperature and CBB activity demonstrated by the mentioned publication. As a climate buffer (Beer et al., 1997), AFS could thus offer a notable contribution when managing CBB infestation. It has also been suggested that because shade modifies the biochemical composition of coffee berries (Vaast et al., 2006; Geromel et al., 2008), this change could make the host colonisation by female CBB more difficult, as the volatile chemicals emitted by red coffee berries might be involved in host colonisation by female CBB (Giordanengo et al., 1993). It is also possible that shade increases the occurrence of CBB (Bosselmann et al., 2009; Rutherford and Phiri, 2006), but does not necessarly result in a higher occurrence on coffee plants.

Concerning infestation with the coffee twig borer (CTB) pest, the results of a recent study suggest that a permanent shade agroecosystem could offer a potential strategy for CTB monitoring (Thapa and Lantinga, 2017). This effect could be due to the fact that CTB adults are more active in the sun, while shade provides unsuitable conditions for flight, mate searching and egg-laying (Thapa and Lantinga, 2017). The reverse of this has been observed with Cerambycidae white coffee borer (WCB). Here, shaded plantations are more suitable for them than sun-exposed ones (Jonsson et al., 2015). Liebig (2017) found that WCB could be managed with AFS only in high altitude plantations and not in those at low and mid altitude (respectively 1100-1400 masl and 1400-1700 masl), although Jonsson et al. (2015) find the contrary. Further research is needed to determine the parametres in a shaded agroecosystem that affect the behaviour of WCB.

CLM is reported to have a less detrimental effect on Arabica coffee shaded plants, since it causes leaf fall towards the end of the dry season in full sun plantations. In these plantations, young leaves emerge during the dry season and not during the rainy season, the same is true for shaded plantations. Interestingly, AFS could modify not only the microclimate but also the physiological development of the coffee plant (Staver et al., 2001).

Regarding CLR infestation, the pattern is more complex. Liebig (2017) demonstrated that CLR infestation varies among AFS in Uganda depending on the biophysical context. CLR infestation could be higher in shaded agroecosystems at mid and high altitude (respectively 1400-1700 masl and 1700-2000 masl), due to lower diurnal temperatures and higher dew points. Jaramillo et al. (2006) found that CLR incidence should be increased in AFS, even if it may not affect the yield. Staver et al. (2001) made the same observation but added that CLR incidence might depend on seasonal humidity fluctuations. The ICAFE's (Instituto del Café de Costa Rica) technical coffee cultivation guide mitigates this observation because CLR incidence may increase only in shade over 40% (ICAFE, 2011).

It has been demonstrated that coffee plants with high K and low N levels in their leaves (Pozza et al., 2001), as well as sun-exposed coffee plantations (Beer et al., 1997; Staver et al., 2001; Salgado et al., 2007; Custódio et al., 2011; Androcioli et al., 2015) favour CLS incidence. Therefore, excessive shade seems to increase the incidence of the fungal disease ALSC (ICAFE, 2011; Serna, 2016). However, as outlined by Liebig et al. (2015), there is an interaction between shading and environmental factors (slope orientation, altitude and temperature) and so the shading impact on ALSC may be considered in the context of site-specific ALSC monitoring. Therefore, one may not suggest that the effect of shade increases or decreases ALSC (Liebig et al., 2015). However for CLS, shade may reduce the incidence of the fungus *Cercospora coffeicola* (Staver et al., 2001). A similar shade effect has been observed by Bedimo et al. (2008) with the fungus *Colletotrichum kahawae*. Their field assessments performed about CBD, which severely attacks African Robusta coffee fields, showed that shade could substantially reduce losses due to this disease.

4.2.2 *Coffea canephora*

Detailed publications on the impact of shelter trees on Robusta coffee PDD are few and far between, but some open up new research avenues. Nesper et al. (2017) pointed out the observed reduction of CBB infestation when Robusta coffee fields were under shade, with the nuance that native shelter trees might be more effective than those non-native, thereby meaning that the type of cover tree used in coffee shaded plantations could be a key condition of a successful CBB management.

Bukomeko et al. (2017) recently pointed out the potential effectiveness of tall mature trees in reducing infestation by the Black coffee twig borer (BCTB), *Xylosandrus compactus* (Eichhoff), a pest which severely affects Robusta coffee plantations, especially in Uganda. In 2012, 68% of Robusta coffee plantations in this country were infested by BCTB (Kagezi et al., 2012). Bukomeko et al. (2017) showed that BCTB infestation on Robusta coffee plants varied with the height, density, species of shelter trees used in coffee AFS, and the resulting climate of coffee AFS. Specifically, tall trees, particularly those which exuded copious amounts of sap when injured, such as *Ficus natalensis* and *Carica papaya*, were the most efficient in reducing BCTB infestation These trees could therefore play a major role in the control of BCTB, probably for the reason that such trees are out of range of the borer's flight and that resources are diluted in AFS, as opposed to resources being more concentrated in a monoculture system that favoured BCTB infestation. According to the climate, Bukomeko's field experiment showed that higher humidity increased the infestation rate of BCTB, since the growth of ambrosia fungi (*Fusarium solani* (Mart.)), associated with BCTB, was favoured by high humidity. The quantity of shade provided by shelter trees is thus not the only parameter to regulate a pest outbreak, as evidenced by Bukomeko. Concerning BCTB control, Egonyu et al. (2017) showed that *Coffea canephora* and *Theobroma cacao* were the crops most preferred by BCTB in Uganda and explained by four simulations based on a potted seedlings experiment that it would be most unlikely that an unpreferred shelter tree such as *Albizia chinensis*, a tree associated with the *Coffea canephora* crop, would increase the level of BCTB infestation. On the contrary, a Malaysian study showed that an excessive quantity of shade could increase BCTB infestation on Robusta coffee (Abbas, 1986).

5. Materials and methods

5.1 Objectives of study

This study aims to assess the effects of shading and different farming practices on PDD in Robusta coffee. The presented trial allows comparison between different AFS in terms of PDD on Robusta coffee. Another objective is to quantify the shade percentage of each of the 5 shade types, to compare the shade percentages and for each shading method, to read its evolution over the day.

5.2 Description of study area

5.2.1 Location

The study will be conducted at the EECA, situated in the canton of La Joya de las Sachas in the province of Orellana in Ecuador. The specific coordinates of the experiment area are: latitude 00°21’31.2’’S, longitude 76°52’40.1’’W, altitude 250 masl, surface 6.48 ha (GPS data).

5.2.2 Soil and climate characteristics

According to Holdridge’s life zones classification system (Holdridge and Tosi, 1967), the climate of the experimental area is a humid, moist forest. Average meteorological characteristics of the area are: annual rainfall 3217 mm, sunshine hours 1418.2, temperature 24°C and relative humidity 91.5% (INAMHI, 2012). In Table 7, recent meteorological data of Joya de las Sachas can be seen. Total rainfall was at its lowest in August with 150.7 mm and highest in May with 358.9 mm according to this table (INAMHI, 2018).

Table 7: Weather data measured between April and August 2018 at the Joya de las Sachas meteorological station

Month	*Mean Max temp. (°C)*	*Mean Min temp. (°C)*	*Mean rainfall per day (mm)*	*Total rainfall (mm)*	*Mean RH (%)*	*Mean RH at 7 am (%)*	*Mean RH at 1 pm (%)*	*Mean RH at 7 pm (%)*
April 18	30.1	20.8	10.7	299.0	85	95	80	85
May 18	30.2	22.0	12.0	358.9	85	90	80	90
June 18	29.5	21.8	7.2	193.5	85	95	80	85
July 18	30.3	21.4	7.3	212.9	85	90	80	85
August 18	30.7	21.7	5.4	150.7	80	90	75	80

September 18	32.1	22.2	4.0	114.6	80	90	70	80

(INAMHI, 2018)

The soil lies in the distal Andean piedmont with a partial volcanic ash cover. As shown in Erreur ! Source du renvoi introuvable.**, the soil is a clay loam in its upper layer with an acid pH and low organic matter content (< 3%). The soils of Joya de las Sachas in general also have a medium cation exchange capacity (11-20 cmol/kg) and a low rate of base saturation (less than 35%), in addition to presenting an effective depth between 20 and 50 cm and 10-25% of coarse particles in its upper layer (Moreno, 2018). These soils are classified as an Andic Dystrudepts (Soil Survey Staff, 2014). Readers will find in Appendix 6. Soil profiles in the EECA experimental field**

the profile of a soil situated in the experimental field.

5.3 Agroforestry systems

An agroforestry system is the combination of a shading method with a farming practice.

5.3.1 Methods of shading

The coffee plants and the shade trees were both planted at the same time in November 2015. Coffee seedlings from 2 recommended clones of *Coffea canephora* 'Robusta' (NP-3013 and NP-2024) were planted in each experimental unit, with 100g of fertilisers (10:30:10), in alternate rows and a low density of 1333 plants per hectare (3 x 2.5 m^2 spacing). The selection criteria of these 2 clones were agronomical, productive and sanitary, e.g. resistance to *Colletotrichum gloeosporioides* (Cristóbal and Mario, 1998). In the present trial, coffee plants were sampled according to the zones defined for assessment of solar radiation (Table 14). As a rule, there should be no significant difference between these 2 clones since they were selected both with and without a low rate of CS severity.

A formation pruning was carried out every 6 months during the first 18 months after plantation, and maintenance pruning carried out after each cycle according to INIAP's recommendations. Pruning wounds were painted with a healing copper paste to prevent fungus entering.

5.3.1.1 Timber

In this shading method, shade is provided by the tree species *Myroxylon balsamum* (MB), grown at a density of 83 plants per hectare (10 x 12 m^2 spacing). This density was specifically chosen, since the Centro Agronómico Tropical de Investigación y Enseñanza in Costa Rica (CATIE) used it for high canopy shelter trees (Picture 11, Boudrot et al., 2016; Schnabel et al., 2017; Segura, 2017). This tree of the Fabaceae family occurs in Central America, as well as in the north and west parts of South America, and is common in tropical forests between 200 masl and 690 masl (Sartori et al., 2015). Although MB is not common in the EAR (Valencia et al., 1994), its presence could provide an additional amount of notable income because its resin is widely used by the cosmetics and

Picture 11. *Myroxylon balsamum* (L.) tree, from surveyed field (in the foreground)

(Source: Kevin Piato)

pharmaceutical industry. MB timber may be used in woodworking (Martínez et al., 2002). This deciduous fast-growing tree is also N-fixing, which is an interesting way of potentially reducing the need for fertilising techniques in coffee plantations (Pasiecznik, 2014). Furthermore, MB is already used in El Salvador as a shelter tree in Arabica coffee plantations and shows good results in terms of economic benefit (Martínez et al., 2002). This specific type of N-fixing tree requires little maintenance since it needs pruning once a year only, which was a clear advantage for the purposes of this research.

Picture 12. *Erythrina spp.*, from surveyed field

(Source: Kevin Piato)

5.3.1.2 Erythrina service

Here, shade is provided by the evergreen legume pantropical tree *Erythrina spp*. (ES), which is probably of South American origin. ES is widely used throughout the world as a shelter tree, especially in cocoa AFS (Kass, 1994). In the present study, ES was grown at a density of 333 plants per hectare (5 x 6 m^2 spacing). This density is lower than that in other experiments with ES (Haggar et al., 2011; López et al., 2012), since the density of coffee plants in the present study was also lower. However, Estívariz and Muschler (1998) used a lower density of ES with a higher density of coffee plants because the experiment was carried out 9 years after plantation and the ES plants were pruned and pollarded during the first year of the AFS coffee cultivation. Generally, the number of trees per hectare is initially higher, then varies over the years to maintain the same shading percentage throughout (Schnabel et al., 2017).

The shade provided by ES varies between 40% and 70% (Staver et al., 2001), due to its high biomass production (Picture 12) and because of this, it is important to prune it frequently to avoid having too much shade. According to species and regions, ES is used in different ways, but the main ones are shade and support, as well as live fences. Generally, its wood is far too light and porous for woodmaking (Kass, 1994).

5.3.1.3 Guaba service

Shade is provided here by the N-fixer *Inga edulis* (IE) tree which, in the present study, was grown at a density of 83 plants per hectare (10 x 12 m^2 spacing). The density of coffee plants per hectare in other studies is much higher but here, the chosen lower density made it easier to reduce the effects of pests and diseases (Siles et al., 2010; Haggar et al., 2011). The evergreen *Inga spp*. tree spreads low (Haggar et al., 2011) and produces edible fruit (Picture 13). Its wood can be used as fuel for domestic and commercial purposes, since it burns well without producing a lot of smoke. This is particularly useful for coffee drying machines and honey production (Barrance et al., 2003).

Staver et al. (2001) reported that *Inga spp*. leaves are resistant to decomposition and may therefore increase the need for mulch to control weed.

Picture 13. Fruit of *Inga edulis*, from surveyed field

(Source: Kevin Piato)

5.3.1.4 Timber and Erythrina service

With this shade method, both MB and ES trees are integrated to the coffee plants at a density of 83 plants/h. MB and ES were planted alternatively. The mentioned density was lower than in previous studies (Haggar et al., 2011; López et al., 2012), it was not reduced after the plantation. Clearly, it is not always the case that enhancing tree diversity reduces PDD (Schroth et al., 2000), since pest and disease outbreaks occur even in highly diverse natural vegetation (Augspurger, 1984). High plant diversity may also imply economic constraints when the choice of crops is strongly influenced by their availability (Schroth et al., 2000).

Nevertheless, polycultures have been described as having a low rate of pests and a high rate of natural enemies (Stamps and Linit, 1997). It is for this reason that Schroth et al. (2000) thinks that the type of species combination is the most important factor to take into account when putting together a strategy for PDD control.

In the present study, the association of MB and ES (never studied before) was chosen since the combination of an evergreen with a deciduous tree may homogenise the amount of shade throughout the year. These are not exotic plants, as will be explored in more detail below, and thus may offer the advantage of improving the quality of coffee (Boreux et al., 2016).

5.3.1.5 Full sun

This strategy leaves the coffee plants completely unshaded. As mentioned above in section 3.1, full sun systems have economical, social and environmental drawbacks. Therefore, this method is generally used in field studies on PDD to compare the effects of a shaded coffee crop to those of an unshaded crop (Ehrenbergerová et al., 2017; Thapa and Lantinga, 2017).

5.3.1.6 Temporary Musa spp. shade

In order to compensate the lack of shade in the first 2 years while permanent shade trees were growing, *Musa spp*. plants were planted to provide temporary shading (Picture 14) at a density of 333 plants per hectare (5 x 6 m^2 spacing). Banana trees were planted in each assessed treatment area, except for those where no permanent shade trees were necessary. The benefits are that this plant provides additional income when the plantain

Picture 14. Temporary shade of *Musa spp*. trees, from surveyed field

(Source: Kevin Piato)

bananas are sold and it grows fast. The disadvantage of *Musa spp*. trees is the damage they cause to coffee plants by falling on them.

5.3.1.7 Pruning schedule

Table 8 presents the main pruning activities carried out on the shade trees. ES trees were frequently pruned because their canopy is very dense as compared to MB trees (Boudrot et al., 2016). Maintenance pruning of IE trees consists of simply cutting the lateral branches once a year, meaning that IE trees do not need a lot of pruning maintenance, whereas as ES trees do.

Table 8: Main pruning activities of shade trees from 2015 to 2018

Date	***Activity***
20.11.2015	Planting of shade trees *Musa spp*. and coffee plants
24.07.2017	Replanting of poor growth *Inga edulis* trees
27.07.2017	Formation pruning of all shade trees. *Erythrina spp*. trees were alternately maintained without pruning to store carbon, and with pruning at a height of 2 m to bring organic matter to the soil
25.08.2017	Maintenance pruning of all shade trees
26.10.2017	Removing selected branches from *Erythrina spp*.
10.04.2018	Formation pruning of *Myroxylon balsamum* trees
27.04.2018	Formation pruning of *Inga edulis* trees

5.3.1.8 Height and crown diameter

Table 9 shows the height and crown diameter of coffee plants and shelter trees in 2018. It is worth noting that *Myroxylon balsamum* trees are much smaller than other shade trees, as to both mean height and mean crown diameter.

Table 9: Height and crown diameter of coffee plants and shelter trees. Mean results covering 10 plants or trees

	Mean height (m)	***Mean crown diameter (m)***
Coffea canephora	1.79	2.16
Myroxylon balsamum	3.02	1.95
Erythrina spp.	6.76	4.18
Inga edulis	7.64	7.00

5.3.2 Farming practices

Within this study, the 5 specified shading methods were combined with 4 farming practices, the latter consisting mainly of fertilising and weeding. Intensive conventional (IC) and moderate conventional (MC) farming practices are detailed in Table 10 and intensive organic (IO) and low organic (LO) farming practices are detailed in Table 11.

Table 10: Application of fertilisers and weed control measures for each conventional farming practice. In red, chemical weed control measures, in green mechanical weed control measures

Conventional			
	Date	**IC**	**MC**
Fertilisation	17.05.2018	Application of synthetic fertilisers: 34 kg/ha of KNO_3, 41 kg/ha of KH_2PO_4, 51 kg/ha of YaraMila Actyva 20-7-10-2MgO-10SO_3, 123 kg/ha of YaraMila Hydran 19-4-19-3MgO, 41 kg/ha of NH_4NO_3. Application of 225 g/coffee plant	Application of synthetic fertilisers: 34 kg/ha of KNO_3, 41 kg/ha of KH_2PO_4, 51 kg/ha of YaraMila Actyva 20-7-10-2MgO-10SO_3, 123 kg/ha of YaraMila Hydran 19-4-19-3MgO, 41 kg/ha of NH_4NO_3. Application of 225 g/coffee plant
Weed control	19.08.2017-25.08.2017	Application of 3.46 l/ha of contact non-selective herbicide paraquat. Mixture: 5.7 ml of paraquat/1 l of water	Application of 3.46 l/ha of contact non-selective herbicide paraquat. Mixture: 5.7 ml of paraquat/1 l of water
	07.10.2017	Elimination of grass weeds with a string trimmer	Elimination of grass weeds with a string trimmer
	20.10.2017	Application of 1.56 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water	
	25.10.2017		Application of 1.73 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water
	20.11.2017	Application of 1.85 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water	
	20.12.2017		Elimination of grass weeds with a string trimmer
	10.01.2018	Application of 2.3 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water	
	17.01.2018		Application of 1.44 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water
	16.02.2018		Application of 1.3 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water

	05.04.2018	Application of 0.92 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water	
	10.04.2018		Elimination of grass weeds with a string trimmer
	18.05.2018	Application of 0.64 l/ha of non-selective herbicide Goal Tender with both contact and residual activity. Mixture: 7.5 ml of Goal Tender/1 l of water	
	15.06.2018	Application of 0.64 l/ha of non-selective herbicide Goal Tender with both contact and residual activity. Mixture: 7.5 ml of Goal Tender/1 l of water	
	16.06.2018		Elimination of grass weeds with a string trimmer
	04.07.2018		Application of 1.4 l/ha of contact non-selective herbicide paraquat. Mixture: 7.5 ml of paraquat/1 l of water
	06.07.2018	Machete manual elimination of residual grass weeds	
	13.07.2018	Application of 0.64 l/ha of non-selective herbicide Goal Tender with both contact and residual activity. Mixture: 7.5 ml of Goal Tender/1 l of water	
	23.08.2018	Machete manual elimination of residual grass weeds	

Table 11: Application of fertilisers and weed control measures for each organic farming practice. In red, chemical weed control measures, in green mechanical weed control measures

Organic			
	Date	**IO**	**LO**
Fertilisation	26.02.2018	Application of organic fertilisers: Eco Abonaza India, semi-composted bird droppings with sawdust mix, 70-73% of organic matter, 3.5-2-3.5. Application of 1 kg/coffee plant	Application of organic fertilisers: Eco Abonaza India, semi-composted bird droppings with sawdust mix, 70-73% of organic matter, 3.5-2-3.5. Application of 1 kg/coffee plant
Weed control	07.10.2017		Elimination of grass weeds with a string trimmer

	01.11.2017	Elimination of grass weeds with a string trimmer	
	05.12.2017	Elimination of grass weeds with a string trimmer	
	20.12.2017		Elimination of grass weeds with a string trimmer
	09.01.2018	Elimination of grass weeds with a string trimmer	
	22.03.2018	Elimination of grass weeds with a string trimmer	
	09.04.2018		Elimination of grass weeds with a string trimmer
	16.06.2018		Elimination of grass weeds with a string trimmer
	25.06.2018	Elimination of grass weeds with a string trimmer	

5.4 Treatments and experimental units

5.4.1 Pest and disease development evaluation

Combining the 5 shading methods with the 4 farming practices resulted in 20 treatments, as shown in Table 12. For a consistent experimental methodology, the number of treatments complies with other field studies assessing the impact of shade on coffee plants (Boudrot et al., 2016; Schnabel et al., 2017). The experimental units which received the treatments specified were sections of 12 x 12 Robusta coffee plants, amounting to 1080 m^2 (thus a total of 144 plants per section). All pest and disease assessments were made on the 36 central square coffee plants only (6 x 6 plants). For the purposes of this research, it was necessary to have such large plots and subplots, as the density of coffee plants and shelter trees was very low (Estívariz and Muschler, 1998) and therefore, much more space was required to equal the sample size in other field studies. In AFS field experiments, experimental units covering several hundred m^2 are usually recommended and used (Dagnelie, 2012; Boudrot et al., 2016; Thapa and Lantinga, 2017). All treatments were replicated 3 times, which is sufficient for this kind of field experiment (Boudrot et al., 2016; Schnabel et al., 2017) with practical, economical and political constraints.

Table 12: Treatments in the experimental study on Robusta coffee pest and disease development

Shading method full name	Shading method abbreviation	Farming practice Treatment			
FULL SUN	SUN	IC **T1**	MC **T2**	IO **T3**	LO **T4**
TIMBER *Myroxylon balsamum* (L.)	TIM	IC **T5**	MC **T6**	IO **T7**	LO **T8**
GUABA SERVICE *Inga spp.*	GUA	IC **T9**	MC **T10**	IO **T11**	LO **T12**
ERYTHRINA SERVICE *Erythrina spp.*	ERY	IC **T13**	MC **T14**	IO **T15**	LO **T16**
TIMBER and ERYTHRINA SERVICE *Myroxylon balsamum* (L.) and *Erythrina spp.*	TaE	IC **T17**	MC **T18**	IO **T19**	LO **T20**

Table 13: Pictures of each treatment in the experimental study on Robusta coffee pest and disease development

Shading method	Farming practice	
FULL SUN	IC	MC
		
	IO	LO
		

<table>
<tr><td rowspan="4">TIMBER
Myroxylon
balsamum (L.)</td><td>IC</td><td>MC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>IO</td><td>LO</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

<table>
<tr><td rowspan="4">GUABA
SERVICE
Inga edulis</td><td>IC</td><td>MC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>IO</td><td>LO</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

	IC	MC
ERYTHRINA SERVICE *Erythrina spp.*		
	IO	LO
		

<table>
<tr><td rowspan="4">TIMBER and ERYTHRINA SERVICE
Myroxylon balsamum (L.) and *Erythrina spp*.</td><td>IC</td><td>MC</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>IO</td><td>LO</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

5.4.2 Shade percentage determination

For this trial, 5 treatments were compared, corresponding to the 5 shade types SUN, TIM, GUA, ERY and TaE. As to assessing pest and disease, the coffee plants used to measure solar radiation were situated among the 36 central square coffee plants of each experimental unit (Figure 8). For each of the 5 assessed shade types, except for the full sun shading method without shelter trees, homogeneous distance zones between shade trees had to been defined, as shown in Table 14; setting up these zones was necessary to be able to consider the heterogeneous shade distribution within the experimental unit. That is how solar radiation was measured in each of these zones.

Figure 8. Representation of the net area (inside the black square) for each of the 5 shading methods assessed, with the extent of each shelter zone:

A spot represents a coffee plant, a triangle a *Myroxylon balsamum* shade tree, a star an *Inga edulis* shade tree, a cross an *Erythrina spp*. shade tree and a crossed circle a *Musa spp*. shade tree. The shading methods represented are respectively (from left to right and top to bottom): Full sun, Timber, Guaba service, Erythrina service, Timber and Erythrina service.

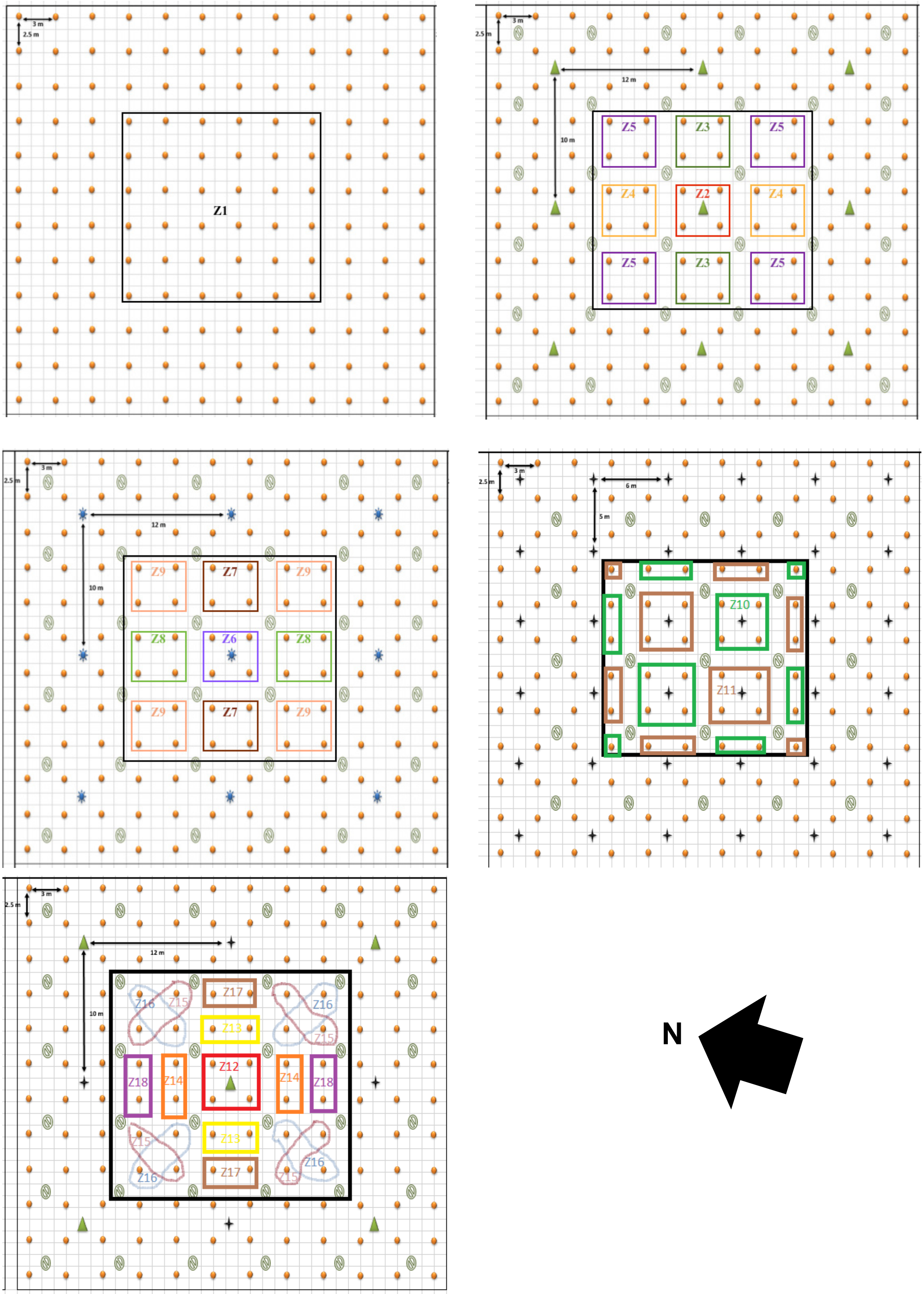


Table 14: Defined zones with homogeneous shade, including distances from coffee plants to shelter trees

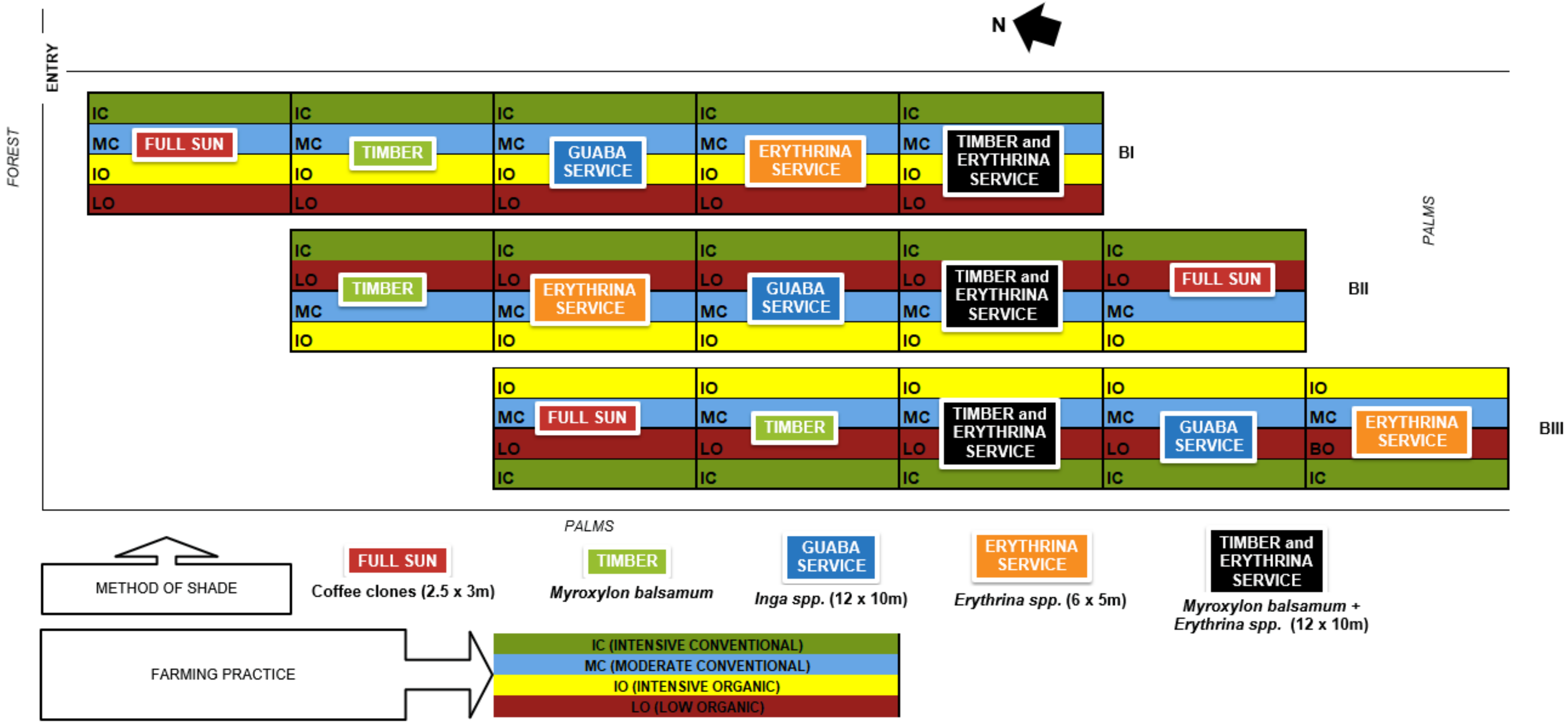
Name of zone	***Shading method***	***Net area %***	***Distance between coffee plants and shelter trees (m)***	***Coffee plants to sample***
Z1	Full sun	100	0	36
Z2	Timber	11.25	1.95	4
Z3	Timber	22.25	4.04	8
Z4	Timber	22.25	4.67	8
Z5	Timber	44.25	5.86	16
Z6	Guaba service	11.25	1.95	4
Z7	Guaba service	22.25	4.04	8
Z8	Guaba service	22.25	4.67	8
Z9	Guaba service	44.25	5.86	16
Z10	Erythrina service	50	1.95 from *Myroxylon balsamum* not pruned 4.03 from *Myroxylon balsamum* pruned	18
Z11	Erythrina service	50	1.95 from *Myroxylon balsamum* pruned 4.03 from *Myroxylon balsamum* not pruned	18
Z12	Timber and Erythrina service	11.1	1.95 from *Myroxylon balsamum* 8.88 from *Erythrina spp*.	4
Z13	Timber and Erythrina service	11.1	4.04 from *Myroxylon balsamum* 6.43 from *Erythrina spp*.	4
Z14	Timber and Erythrina service	11.1	4.67 from *Myroxylon balsamum* 7.60 from *Erythrina spp*.	4
Z15	Timber and Erythrina service	22.25	7.70 from *Myroxylon balsamum* 5.86 from *Erythrina spp*.	8
Z16	Timber and Erythrina service	22.25	5.86 from *Myroxylon balsamum* 7.70 from *Erythrina spp*.	8
Z17	Timber and Erythrina service	11.1	6.43 from *Myroxylon balsamum* 4.04 from *Erythrina spp*.	4
Z18	Timber and Erythrina service	11.1	7.60 from *Myroxylon balsamum* 4.67 from *Erythrina spp*.	4

5.5 Experimental designs

5.5.1 Evaluation of pest and disease development

The set-up consists of a completely randomised block-design, with the shade method as the main plot and the farming practice as the subplot. This design is used when an experiment involves factors that are difficult to apply to small experimental units. As shown in Figure 9, two sets of treatments are randomised across each other in strips (split-block design). The shading method factor extends vertically and the farming practice factor horizontally. Each block represents one replication. This design is more suitable to identify the interaction between two factors than relying on the main overall effect of these individual factors (Dagnelie, 2012).

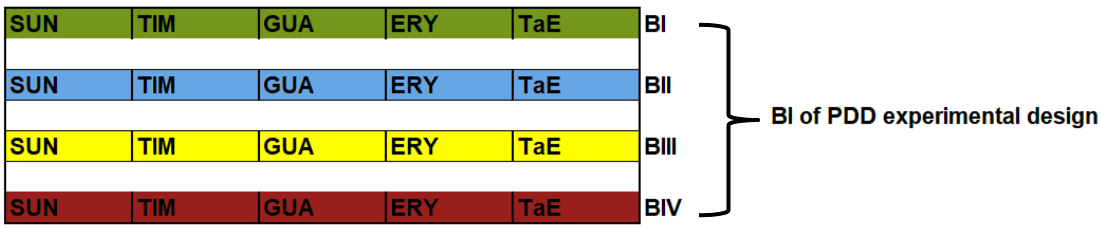
Figure 9. Experimental design for the development of Robusta coffee pest and disease



5.5.2 Determination of shade percentage

The measurements were made only in the first block of the experimental design used for PDD assessment. In this first block, each horizontal line frames a new block. The farming practice factor was assimilated to the block factor, since the farming practice was not to significantly impact the shade percentage, the shelter trees being pruned. This new experimental design was replicated 4 times because in the first block used for PDD assessments, the same shading method was repeated 4 times (4 farming practices) (Figure 10). Thus, a randomised complete blocks design was used to assess shade quantity.

Figure 10. Experimental design to determine Robusta coffee shade percentage



5.6 Collection of field data

5.6.1 Evaluation of pest and disease development

In the present trial, 9 response variables were assessed monthly in each experimental unit, from July to September 2018. The first measurements were made on 12th and 13th July, the second on 13th and 14th August and the third on 3rd September. These response variables are the incidence rates of the cercospora leaf spot (CLS), *Colletotrichum spp*. (CS), *Phoma spp*. (PS) and thread blight (TB) disease, the infestation rates of coffee berry borer (CBB), coffee leaf miner (CLM) and brown twig beetle (BTB), CS severity and the presence of *Beauveria bassiana* (BB). The following pest and disease assessments are mainly based on the INIAP protocol for crop health characterisation (Cañarte et al., 2016). In each middle coffee square, 9 plants were randomly selected. These 9 plants had to be selected in the shade zones defined in chapter 5.4.2, so as to obtain a sample with Robusta coffee plants under different levels of shade. The results were thus more representative of the field's heterogeneity. A total of 540 coffee plants were assessed monthly.

As mentioned above, all assessments were recorded within 1-2 days each month, thanks to field teamwork, with the purpose of avoiding PDD differences between the first day and the last day of evaluation. Three teams were set up with a minimum of 3 people, 4 if possible. In each team, one person wrote the results and the 2 other people performed evaluations. Among the two evaluators, one counted the fruit and branches to determine the rates of BTB and CBB infestation, as well as BB presence. The other evaluator counted the leaves and determined the rates of CS, PS, CLS, TB incidence, as well as the CLM infestation rate; he also collected 6 leaves per coffee plant so as to later determine CS severity through ImageJ. When the team numbered 4 people, the fourth one located the plants and collected the 6 leaves per coffee plant for the assessment of CS severity. For each block of coffee plantations, the treatments were randomly assigned to each team member to avoid only one person assessing the same plot, or subplot, from the same block, to avoid any measurement bias. The same team evaluated the same block in August and September.

After sampling and plant identification in the field with red tags, the evaluation itself was performed. One evaluator randomly selected 3 branches of coffee plants: one from the low section, one from the middle section and one other from the upper section of the plant. After that, the short internode was identified in each branch in order to distinguish the current year's leaves from those of the past year. Then, all the healthy leaves from the short internode right to the tip of the branch were counted by the evaluator. Those leaves infected by CS, PS, CLS, TB and infested by CLM were also counted in this same section of the branch. This methodology (Avelino et al., 1991) was used for the reason that the older leaves fall more easily than the younger ones, so if the older leaves had also been counted, disease would probably have been over-estimated. The other evaluator counted all the branches on one stem, as well as all the branches with BTB damage. This same evaluator also counted all the fruit on 2 branches randomly selected but displaying enough fruit: one from the low section and one from the middle section. Then all the fruit showing a CBB hole and BB presence were counted. Both evaluators communicated the results to the writer who wrote them all in the field data sheet (**Erreur ! Source du renvoi introuvable.**).

5.6.2 Determination of *Colletotrichum spp.* severity by image processing

For each Robusta coffee plant assessed, 6 leaves were collected from the same branches as used for PDD assessment: 2 from the low section, 2 from the middle section and 2 others from the upper section of the plant. In each case, the 2 leaves were picked immediately after the short internode. The leaves were collected on 12th and 13th July 2018.

Then all the leaves were scanned with the multi-function printers EPSON L555 Series and Hemlett-Packard HP Color Laser Jet CM1312 MFP with a resolution of 200 dpi.

After that, all the pictures of 3240 leaves were processed through the ImageJ programme to determine the total leaf area and the total leaf necrotic area. To determine the total leaf area damaged by CS only, the following filter of the function “Adjust color balance” was used: Lab-white, L*= 7-95/a*= 124-243/b*= 0-255. Only the necroses bigger than 500 pixels were considered.

5.6.3 Shade percentage determination

In order to quantify the shade percentage of the 5 shade types that were assessed and to find between them significant differences in shade percentage, total irradiation measurements were made by using an Apogee MP-200 silicon-cell pyranometer (https://www.apogeeinstruments.com/mp-200-pyranometer-separate-sensor-with-handheld-meter/) with a separate sensor and a leveling plate. This pyranometer can display and store measurements in W/m^2. Its spectral range is from 360 to 1120 nm. The amount of solar radiation that each area receives under total irradiation, is measured. Part of that radiation will be used by the trees for photosynthesis, the rest will either be reflected or absorbed, impacting temperature and relative humidity, which also influences PDD. With the aforementioned radiation sensor, it is possible to measure shade within the environmental context, which will provide evidence as to how shade might impact PDD. Photosynthetically active radiation (PAR) will not be determined, since this parameter is used rather to assess coffee production or vegetative growth (Rodríguez et al., 2014), which is not a primary objective of the present trial. To avoid the interference of self-shading coffee bushes (Long et al., 2015) and to ensure that the measurements reflect shading from shelter trees only, all values were measured at the edge of the foliage, in other words at the tip of the branches and at a height of 2 m.

For each of the 5 assessed shade types, the average shade percentage was determined by taking 5 measurements of solar radiation for each coffee plant assessed: one each at the apex, the east, the west, the north and the south of the plant. This is because there are solar radiation variations on different sides of the coffee plant due to its consistent diameter (average 215.5 cm). Measurements at the 4 cardinal points were also gathered with the densitometer which measures canopy coverage (Lemmon, 1957). Once these 5 measurements had been made, one more more was made in full sun as reference to work out the shade percentage.

The values were measured with the solar equipment on 1 randomly selected coffee plant in each zone defined in Table 14, except for the SUN shading method, in which 2 coffee plants were ramdomly selected. In total, 76 Robusta coffee plants were evaluated. Before use, the pyranometer had to be prepared. First, the wooden post was pegged and 2 small spirit levels were tied with adhesive tape on 2 sides of the post in such a way that the 2 spirit levels were centered in the level indicator.

Picture 15. Pyranometer mounted on a wooden post, from surveyed field

(Source: Kevin Piato)

Secondly, when the 2 spirit levels were centered, the pyranometer bolted to the leveling plate was inserted into a shallow cavity at the top of the wooden post in such a way that the spirit bubble of the leveling plate was centered in the level indicator. The pyranometer was then ready to be used. Before each measurement, the 2 evaluators had only to adjust the 2 lateral spirit levels.

Measurements with the pyranometer must be taken in sunlight only and the sun not be covered by clouds.

For the best reading of how shade varies throughout the day, all measurements on the 76 coffee plants were recorded at the following periods of the day: 9am-10.30am, 11.30am-1pm, 2pm-3.30pm. This resulted in 4 average shade percentages for each shading method and each period of the day.

5.7 Data processing

5.7.1 Evaluation of pest and disease development

5.7.1.1 Data cleansing

First, when the total number of branches, fruits and leaves was nil, these data were deleted and not used to calculate any disease incidence or pest infestation. Secondly, all unlikely data were also deleted, for instance when the number of fruit with CBB was higher than the total number of fruits assessed. Thirdly, in order to work with a standard value for the total numbers of branches, fruits and leaves, all values between the 10^{th} and 90^{th} percentile were taken into consideration and the other values deleted. Fourthly, all mean values obtained (infestation, incidence and presence rates) between the 5^{th} and 95^{th} percentile were taken into consideration and the other values deleted. These last two steps were also necessary to exclude errors due to bad identification of the short internode and the tendency to select branches with a small number of fruit in order to gain time. This cleansing was performed for all variables except CS severity.

As to the rate of CS severity, another cleansing was performed since the values were more accurate, thanks to the use of ImageJ. All CS severity rates between the 1st and 99^{th} percentile were taken into consideration, and all other values deleted. This cleansing was necessary to dismiss all leaves that were damaged after the harvest or picked behind the short internode.

5.7.1.2 Calculations

To calculate the disease incidence rates of CS, PS, CLS and TB, the following formula was used:

Inc (%) = (n/N) x 100

Inc (%) = incidence (%),

n = number of infected leaves,

N = total number of leaves

To asses pests, the following formula was used to calculate the CBB infestation rate:

Inf (%) = (n'/N') x 100

Inf (%) = infestation (%),

n' = number of cherries where CBB was present,

N' = total number of cherries assessed

Either a CBB, a hole or holes near the apex of the cherries proved the presence of CBB.

BTB infestation rate was estimated by counting all the main branches of a stem and all the branches with galleries and/or blackenings on the branches, showing the presence of BTB. The following formula was used to calculate BTB infestation rate:

Inf (%) = (r/R) x 100

Inf (%) = infestation (%),

r = number of branches where BTB was present,

R = total number of branches assessed

The procedure relating to the estimation of the CLM infestation rate involved identifying the presence of leaves with active leaf-miners and/or with brown spots with separate epidermis. The following formula was used to calculate the CLM infestation rate:

Inf (%) = (r'/R') x 100

Inf (%) = infestation (%),

r' = number of leaves with CLM leaf damage,

R' = total number of leaves assessed

The rate of BB presence was calculated with the following formula:

Pre (%) = (b/B) x 100

Pre (%) = presence (%),

b = number of cherries perforated by CBB with BB,

B = total number of cherries perforated by CBB

BB fungus was identified when there was a white blanket above the CBB hole. To determine CS severity rate, the following formula was used:

Sev (%) = (s/S) x 100

Sev (%) = severity (%)

s = total necrotic area of leaves,

S = total area of leaves

5.7.2 Determination of shade percentage

The shade percentage was calculated with the following formula, for each of the 76 Robusta coffee plants assessed: shade percentage = (1- (average W under shade / W in full sun))(100). An average shade percentage per plant was thus obtained.

The second step was to calculate the average shade percentage per zone with the average shade percentages obtained in the first step.

The third step was to calculate the weighted average shade percentage of the experimental unit with the following formula: ((average shade percentage of Z_1)(net area percentage of Z_1) + (average shade percentage of Z_2)(net area percentage of Z_2) + … + (average shade percentage of $Z_{\text{number of zones of the shading method}}$)(net area percentage of $Z_{\text{number of zones of the shading method}}$))(100).

The fourth step was to calculate the daily average shade percentage of the experimental unit.

5.8 Statistical analysis

5.8.1 Evaluation of pest and disease development

Minitab® 18 Statistical Software was used for statistical analysis. Data was analysed using mixed linear models (LMM) for a split-block design with 3 repetitions, treatments as fixed effect and blocks as random effect. The following model was used for data analyses (Di Rienzo et al., 2011):

$$y_{ijk} = \mu + \sigma_i + \phi_j + \lambda_{ij} + b_k + f_{ki} + c_{kj} + e_{ijk}$$

y_{ijk} = observed response to the ith shade method, jth = farming practice and kth level of block factor (ramdom effect),

μ = overall average of the response,

σ_i = ith effect of the shade method,

ϕ_j = jth effect of farming practice,

λ_{ij} = interaction between the factors shade method and farming practice,

b_k = kth level of block factor or the error within an entire block,

f_{ki} = effect of block k in the ith shade method (ramdom effect) or the error within a plot,

c_{kj} = effect of block k in the jth farming practice (ramdom effect) or the error within a subplot, and

e_{ijk} = residual error.

To find any statistically significant differences between the treatments assessed, LMM was applied, followed by Tukey's test for multiple comparisons with a significance level of α=0.05. In order to use LMM, residual normality was checked by using quantile-quantile (Q-Q) plots. Homogeneity of variance was checked by graphical representation of residuals versus predictor plots. If the residual normality criterion was not fulfilled, the data were log-transformed. As the homogeneity of variance was always fulfilled, it was not necessary to adjust the variables with heteroscedastic models.

If the expected mean squares given by Minitab when performing the LMM, were in the same order of magnitude (the ratio of the max mean square and the min mean square not exceeding 2), Dagnelie's assumption was applied. This assumption allows to consider the split-block design as a randomised complete blocks design (Dagnelie, 2012).

5.8.2 Shade percentage determination

In the shade percentage assessment trial, *Minitab® 18* Statistical Software was also used for statistical analysis. Data were analysed using LMM for a randomised complete blocks design with 4 repetitions and 5 treatments (SUN, TIM, TyE, ERY and GUA), shading method in terms of average shade percentage as fixed effect and blocks as random effect. Tukey's test for multiple comparisons was also applied with a significance level of α=0.05. In order to use LMM, residual normality was checked with quantile-quantile (Q-Q) plots. Homogeneity of variance was checked by graphical representation of residuals versus predictor plots. If the residual normality criterion was not fulfilled, the data were log-transformed. If the homogeneity variance criterion was not fulfilled and in order to use ANOVA with 2 factors, the Friedman non-parametric test was applied to illustrate a difference between the treatments.

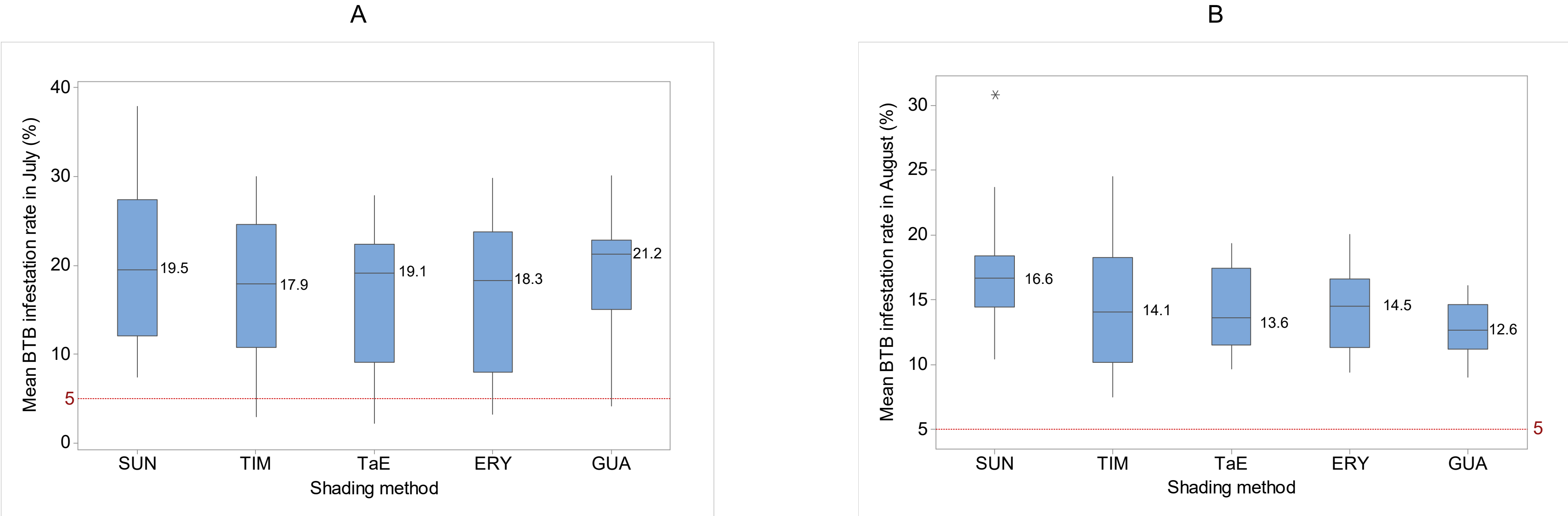
To compare the average shade percentages of the 3 periods in a day, the same randomised complete blocks design was applied, the 3 factors being the shading method, the period in a day and the block.

6. Results

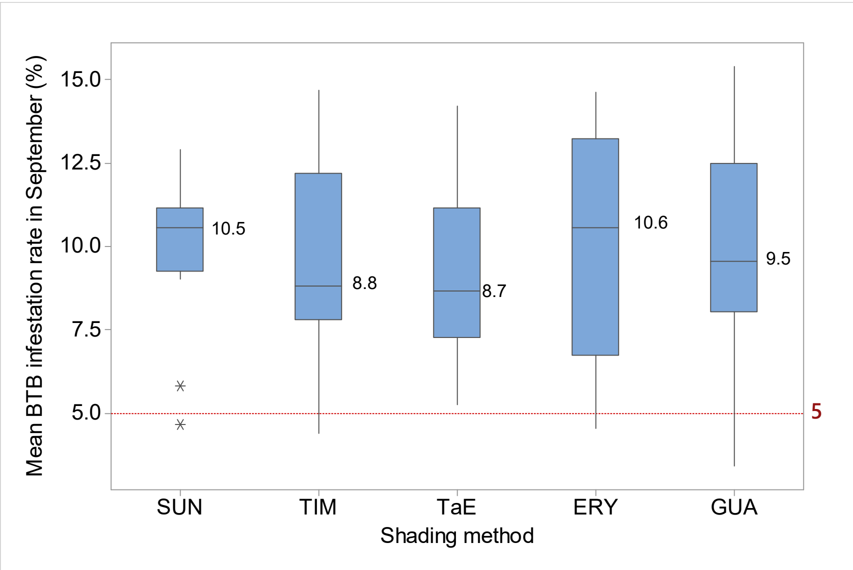
6.1 *Xylosandrus morigerus* infestation

Figure 11 shows that the mean BTB infestation rate does not greatly differ from one shading method to another. The infestation was above the economic threshold during all the months assessed. However, the graphs do denote a global continuous decrease of the mean BTB infestation during the months assessed.

Figure 11. Graphics of the mean *Xylosandrus morigerus* infestation rate in relation to the shading method:
A-C: Box and whisker plots of the mean *Xylosandrus morigerus* infestation rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: histogram of the mean *Xylosandrus morigerus* infestation rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.



C



D

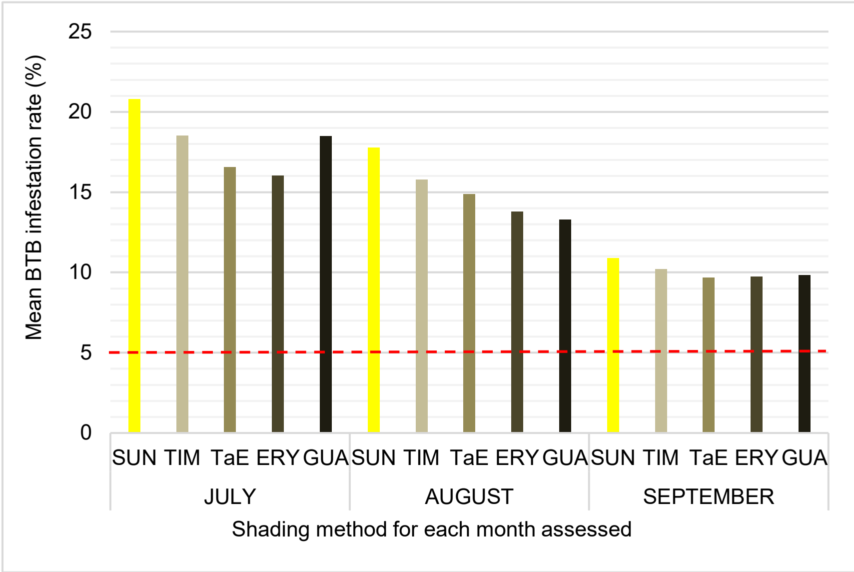
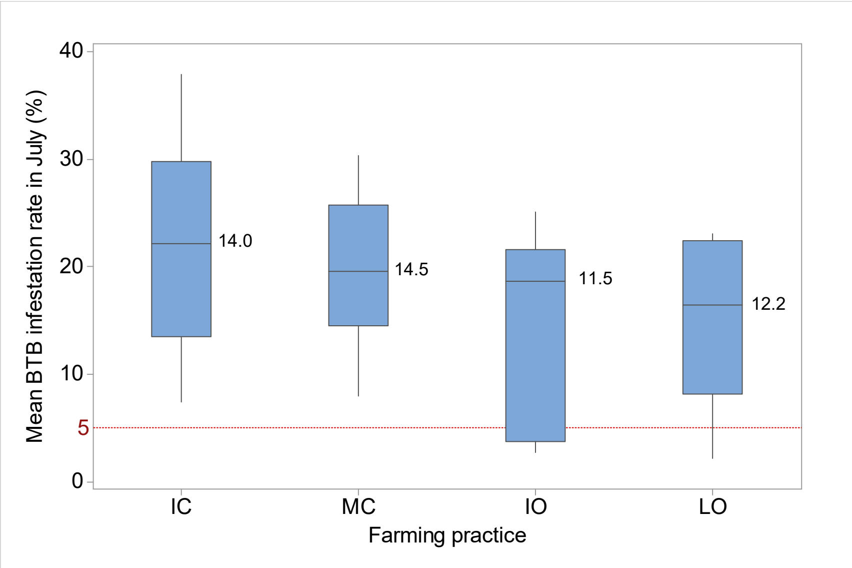


Figure 12 indicates that the organic farming practices (IO and LO) present a lower BTB infestation rate than the conventional farming practices (MC and IC). The infestation was above the economic threshold during all the months assessed. However, the graphs denote a global continuous decrease of the mean BTB infestation during the months assessed.

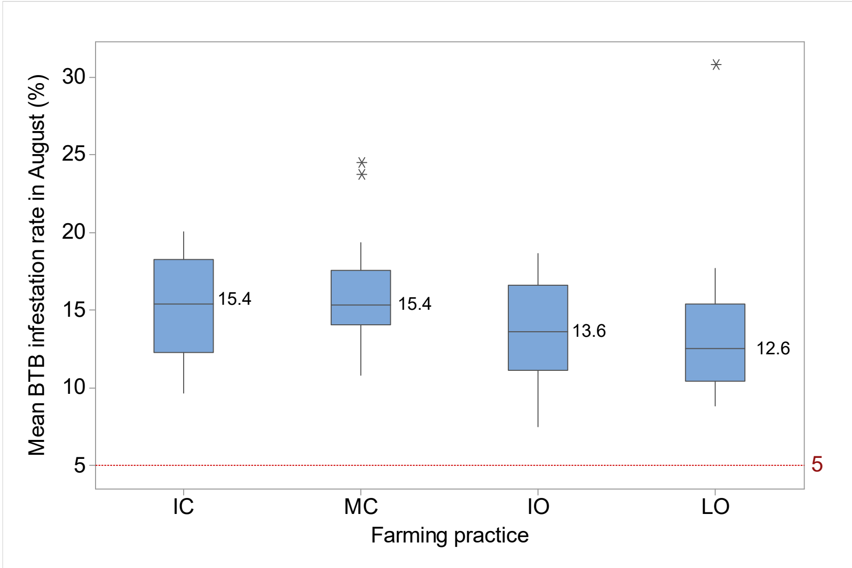
Figure 12. Graphics of the mean *Xylosandrus morigerus* infestation rate in relation to the farming practice:

A-C: Box and whisker plots of the mean *Xylosandrus morigerus* infestation rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Xylosandrus morigerus* infestation rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

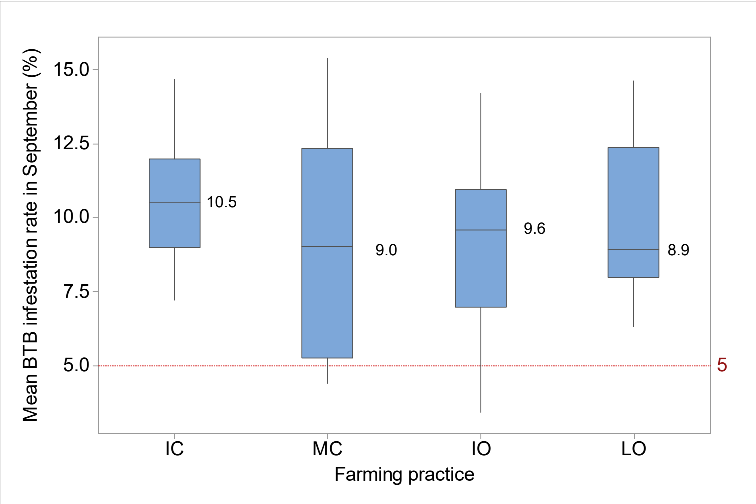
A



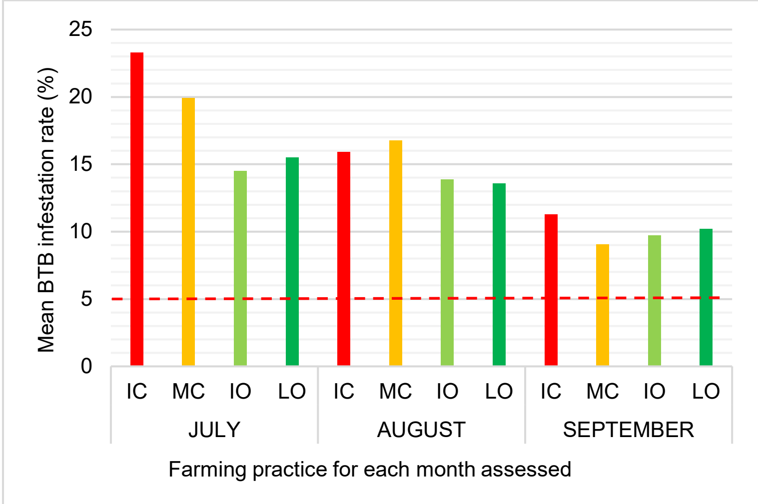
B



C



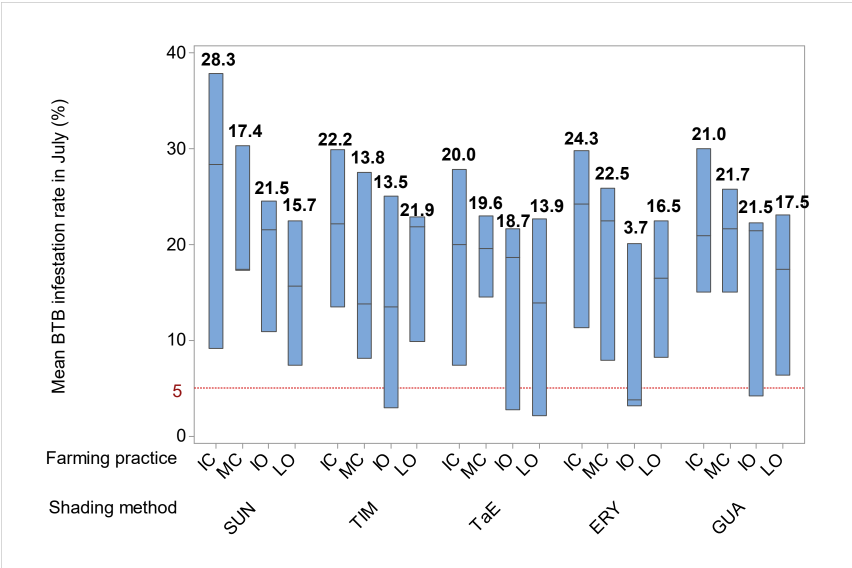
D



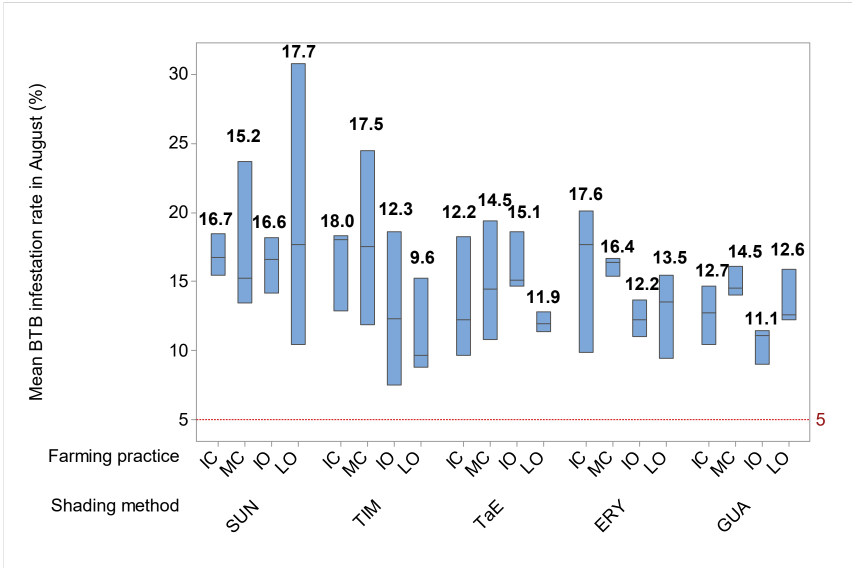
In Figure 13, the graphs show that the worst AFS systems with respect to BTB infestation in July, August and September are as follows: SUN-IC with a median 28.3%, SUN-LO with a median 17.7% and GUA-MC with a median 12.5%. The best AFS systems are respectively: ERY-IO with a median 3.7%, TIM-LO with a median 9.6% and TIM-IO with a median 8.3%. It is interesting to point out that 50% of ERY-IO AFS data are below the economic threshold of 5%. Furthermore, the graphs denote a global continuous decrease of BTB infestation during the months assessed.

Figure 13. Graphics of the mean *Xylosandrus morigerus* infestation rate in relation to agroforestry systems:
A-C: Box and whisker plots of the mean *Xylosandrus morigerus* infestation rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Xylosandrus morigerus* infestation rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

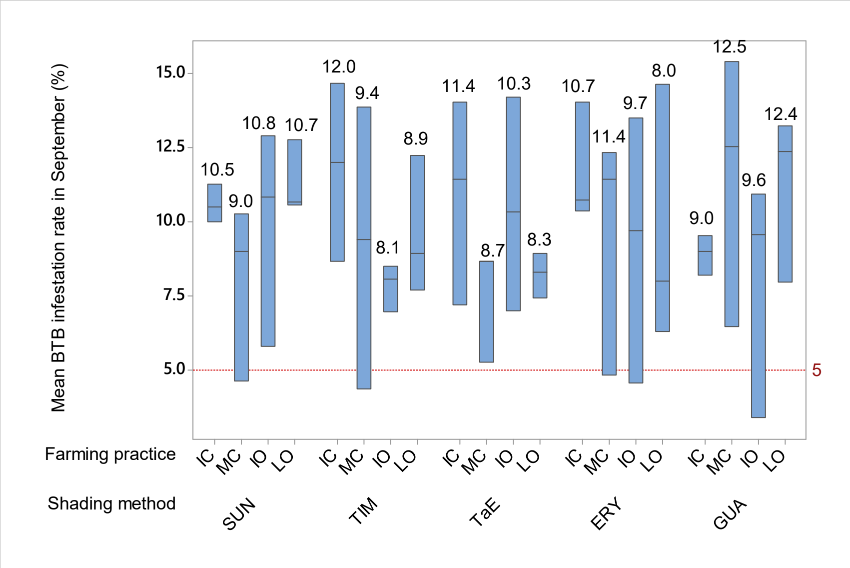
A



B



C


Mean BTB infestation rate in September (%)
15.0
12.5
10.0
7.5
5.0
5
10.5
9.0
10.8
10.7
12.0
9.4
8.1
8.9
11.4
8.7
10.3
8.3
10.7
11.4
9.7
8.0
9.0
12.5
9.6
12.4
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

D

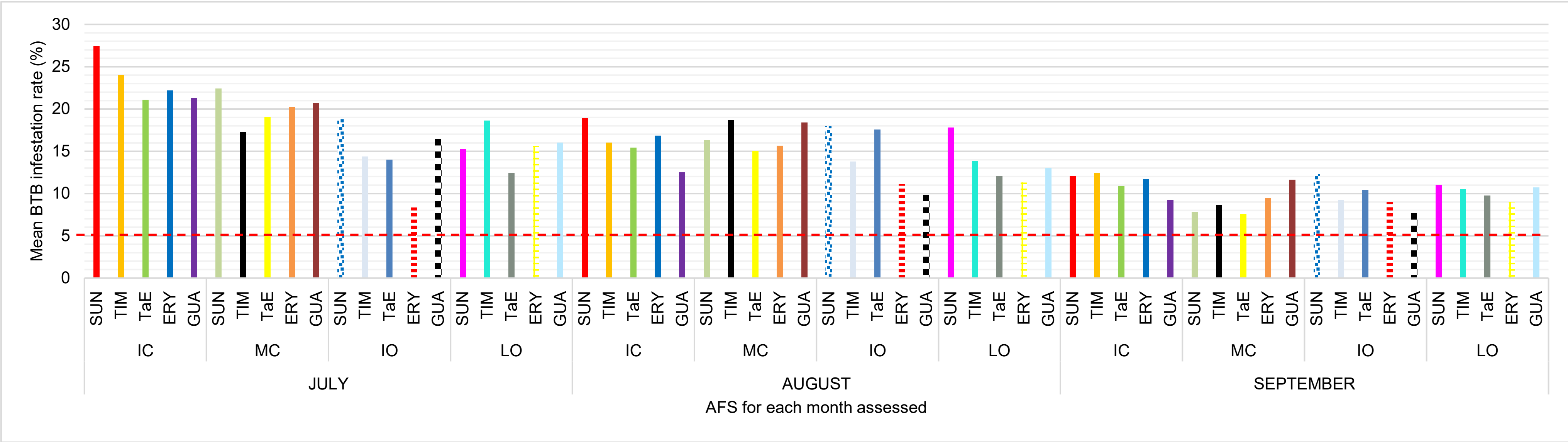


Table 15 shows that the shading method significantly impacts the mean BTB infestation rate in August (p-value= 2.7%) and that the farming practice significantly impacts the mean BTB infestation rate in July (p-value= 0.6%).

Table 15: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Xylosandrus morigerus* infestation rate (%). P-values below 5% are statistically significant and indicated in bold.

	p-value		
	July	August	September
Shading method	0.161	**0.027**	0.889
Farming practice	**0.006**	0.142	0.079
Shading method*farming practice	0.728	0.498	0.125

According to July's measurements shown in Table 16, experimental units applying an IC farming practice had a mean BTB infestation rate statistically and significantly between 3%-12% higher than those applying an IO farming practice, this being in addition to having a mean BTB infestation rate statistically and significantly between 2%-11% higher than those applying an LO farming practice. Further, experimental units applying an MC farming practice had a mean BTB infestation rate statistically and significantly between 1%-9% higher than those applying an IO farming practice. Results in August showed that experimental units applying an SUN shading method had a mean BTB infestation rate statistically and significantly between 1%-9% higher than those applying a GUA shading method.

Table 16: Results of Tukey's tests for multiple comparison intervals of the farming practices in July and the shading methods in August in relation to the mean *Xylosandrus morigerus* infestation rate (%). P-values below 5% are statistically significant and indicated in bold.

July		
Farming practice		
Difference between mean rates	*95% confidence intervals (mean BTB infestation rate difference in %)*	*Adjusted p-value*
IC-MC	(-1.8; 6.77)	0.415
IC-IO	(3.14; 11.71)	**< 0.001**
IC-LO	(2.04; 10.61)	**0.002**
MC-IO	(0.65; 9.22)	**0.018**
MC-LO	(-0.45; 8.13)	0.093
IO-LO	(-5.39; 3.19)	0.901
August		
Shading method		
Difference between mean rates	*95% confidence intervals (mean BTB infestation rate difference in %)*	*Adjusted p-value*
SUN-TIM	(-1.04; 6.94)	0.233

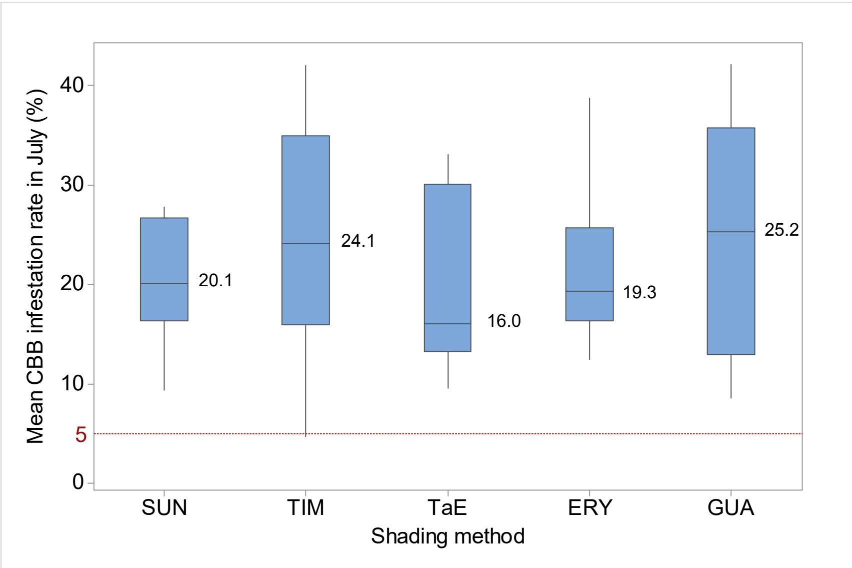
SUN-TaE	(-0.53; 7.44)	0.116
SUN-ERY	(-0.7; 7.28)	0.148
SUN-GUA	(0.68; 8.65)	**0.015**
TIM-TaE	(-3.48; 4.49)	0.996
TIM-ERY	(-3.65; 4.33)	0.999
TIM-GUA	(-2.28; 5.7)	0.735
TaE-ERY	(-4.15; 3.82)	1
TaE-GUA	(-2.78; 5.19)	0.908
ERY-GUA	(-2.61; 5.36)	0.86

6.2 *Hypothenemus hampei* infestation

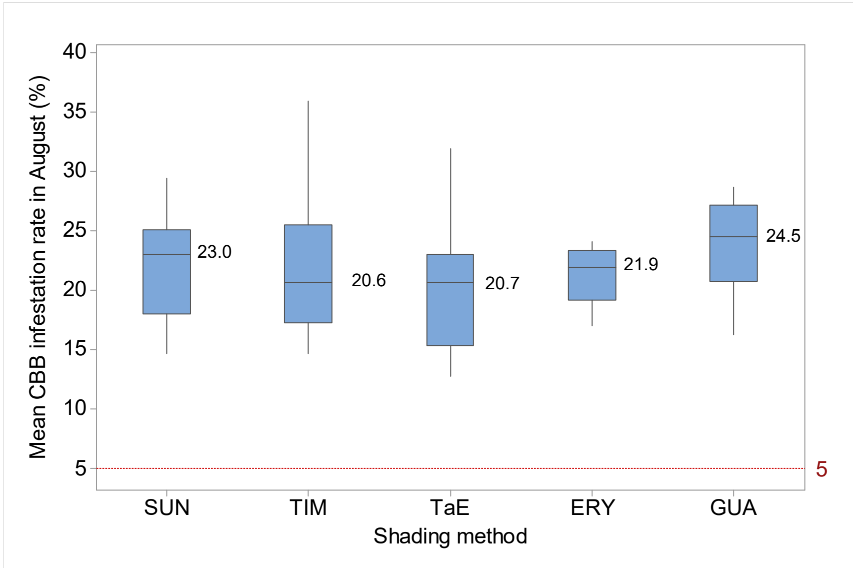
Figure 14 shows that the CBB infestation rate does not greatly differ from one shading method to another except for the month of July, during which the TaE shading method showed a mean CBB infestation rate markedly lower than the other shading methods. The infestation was above the economic threshold during all the months assessed.

Figure 14. Graphics of the mean *Hypothenemus hampei* infestation rate in relation to the shading method: A-C: Box and whisker plots of the mean *Hypothenemus hampei* infestation rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Hypothenemus hampei* infestation rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

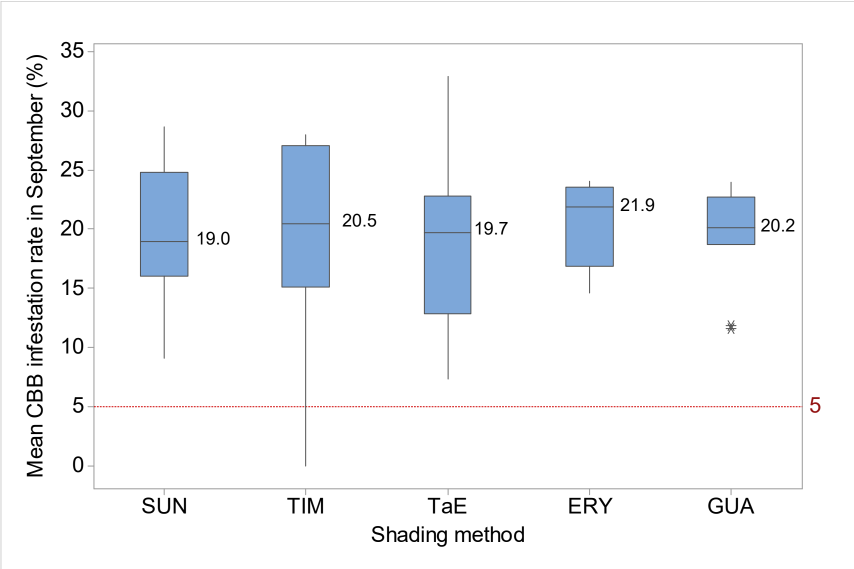
A



B



C



D

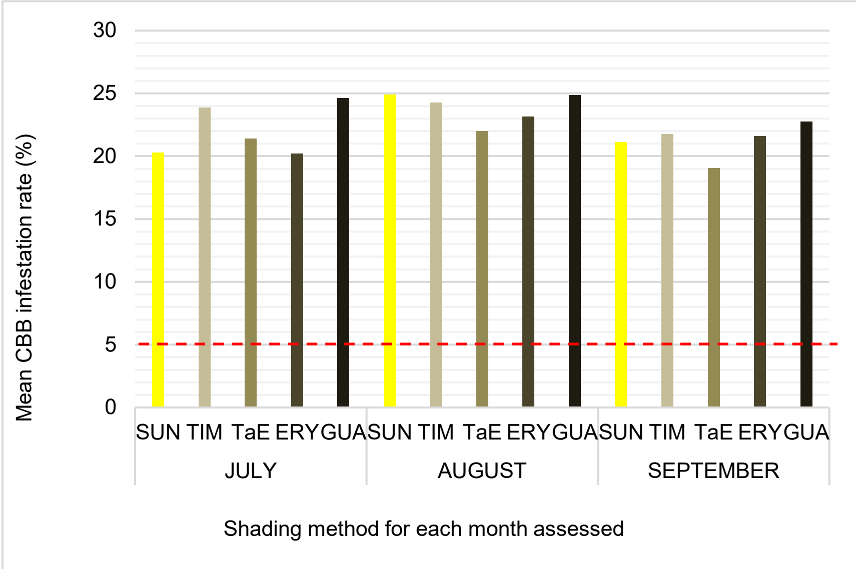
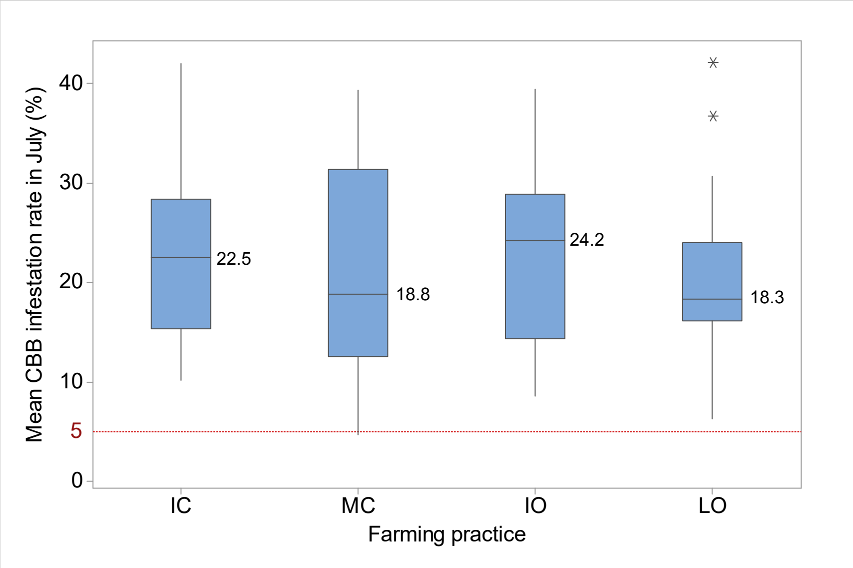


Figure 15 indicates that MC, IO and LO farming practices present a lower CBB infestation rate than the IC farming practice for both August and September. In July, the MC and LO farming practices presented a lower CBB infestation rate than the IC and IO farming practices. Infestation was above the economic threshold during all the months assessed.

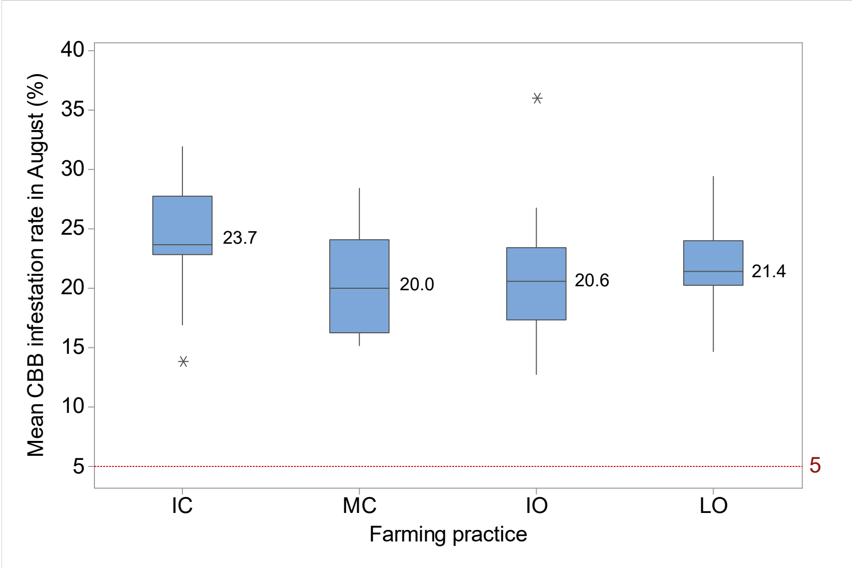
Figure 15. Graphics of the mean *Hypothenemus hampei* infestation rate in relation to the farming practice:

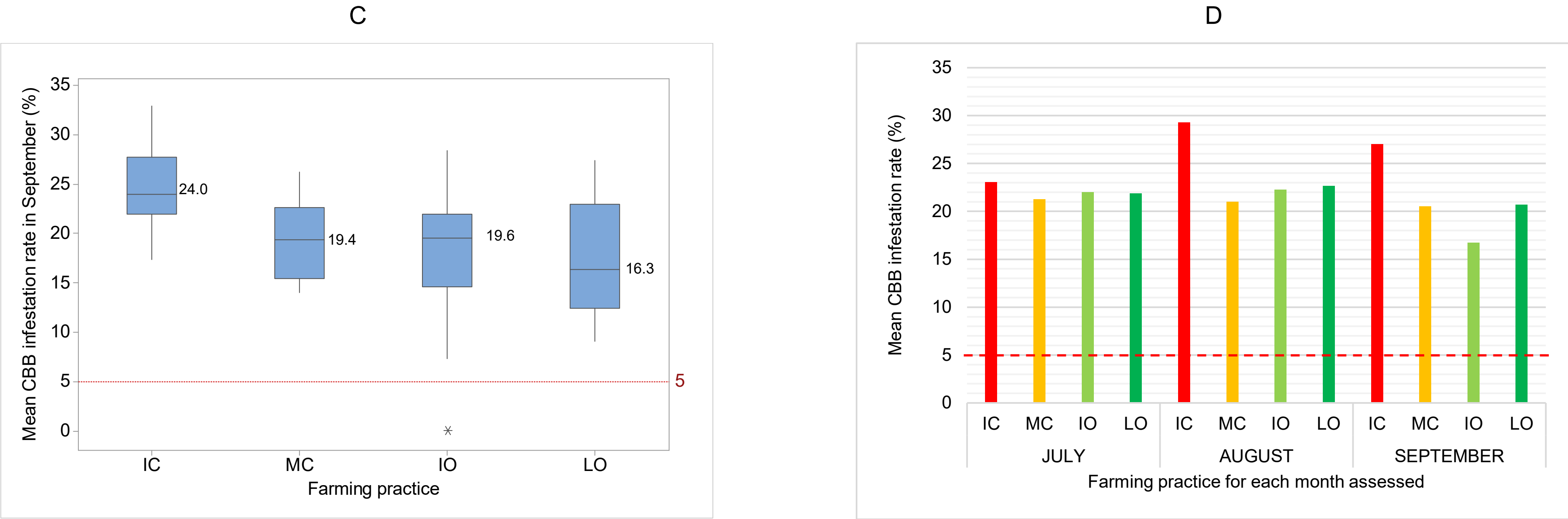
A-C: Box and whisker plots of the mean *Hypothenemus hampei* infestation rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Hypothenemus hampei* infestation rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

A



B

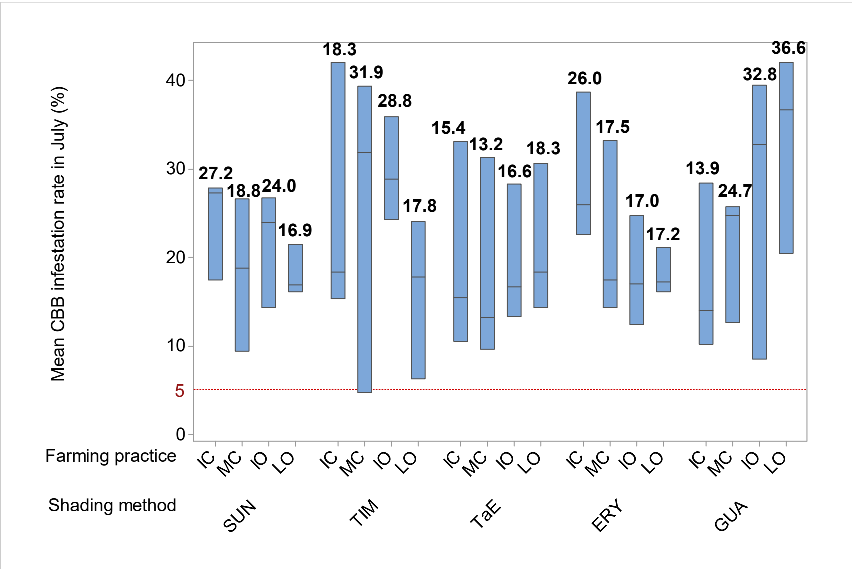




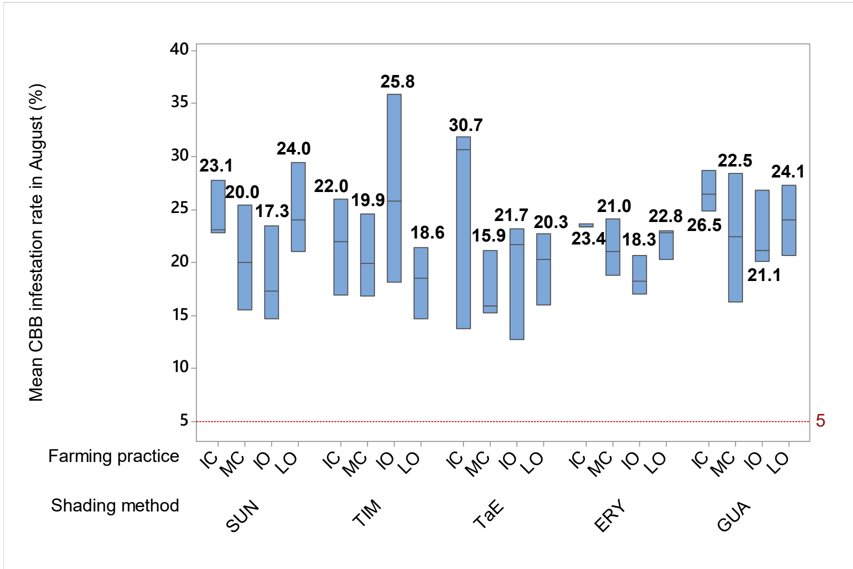
In Figure 16, the graphs show that the worst AFS systems with respect to CBB infestation in July, August and September were as follows: GUA-LO with a median 36.6%, TaE-IC with a median 30.7% and TIM-IC with a median 27.8%. The best AFS systems were as follows: TaE-MC with a median 13.2%, TaE-MC with a median 15.9% and TaE-LO with a median 12.5%. Further, the histogram denotes that the mean CBB infestation rate was higher with the IC farming practice in both August and September.

Figure 16. Graphics of the mean *Hypothenemus hampei* infestation rate in relation to agroforestry systems: A-C: Box and whisker plots of the mean *Hypothenemus hampei* infestation rate (%) in relation to the agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Hypothenemus hampei* infestation rate (%) in relation to the agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

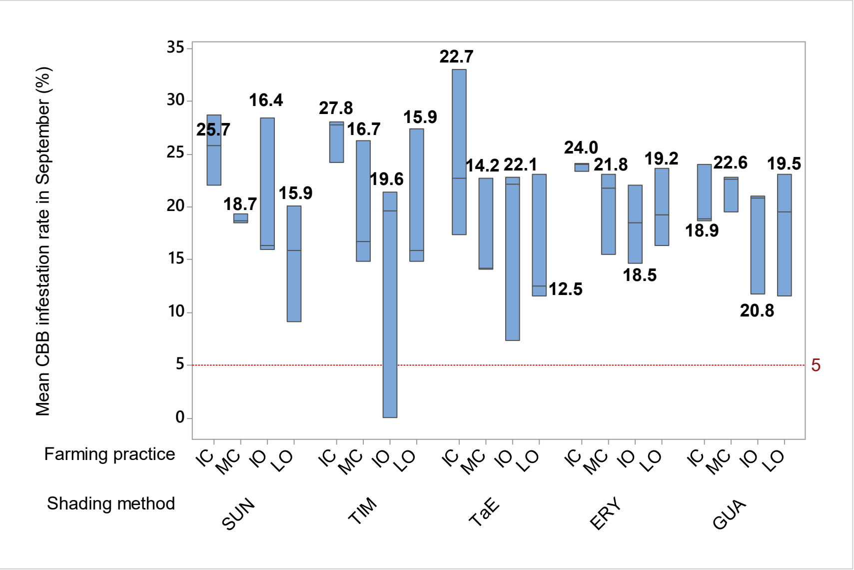
A



B



C



Mean CBB infestation rate in September (%)
35
30
25
20
15
10
5
0
25.7
18.7
16.4
15.9
27.8
16.7
19.6
15.9
22.7
14.2
22.1
12.5
24.0
21.8
18.5
19.2
18.9
22.6
20.8
19.5
5
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

D

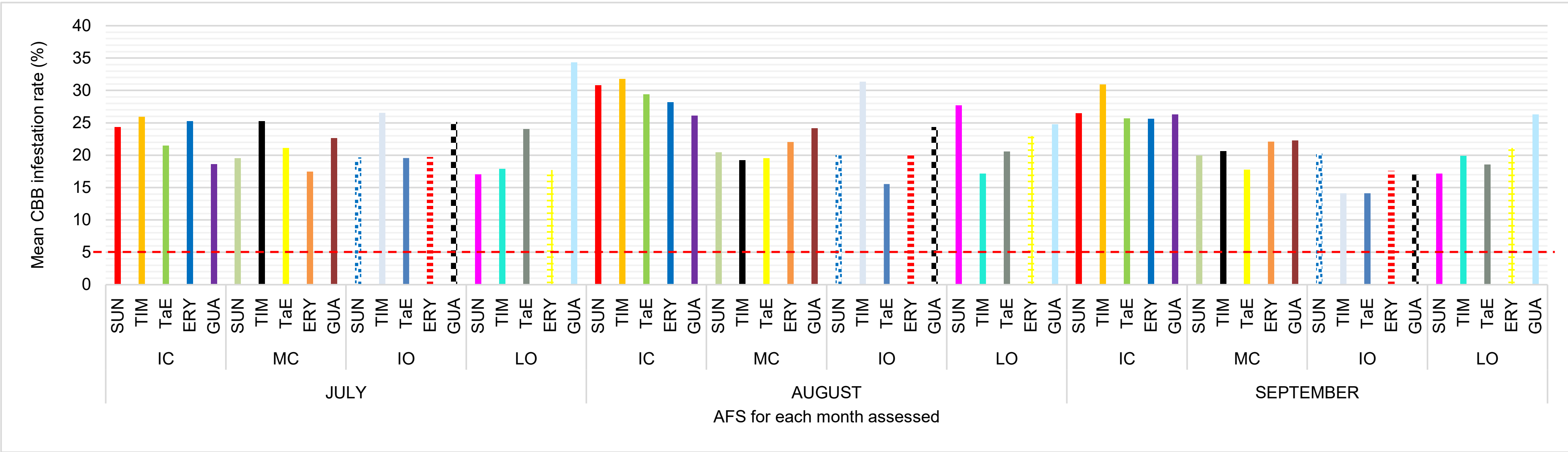


Table 17 shows that the farming practice significantly impacted the mean CBB infestation rate in September (p-value= 0.2%).

Table 17: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Hypothenemus hampei* infestation rate (%). P-values below 5% are statistically significant and indicated in bold.

	p-value		
	July	August	September
Shading method	0.524	0.728	0.917
Farming practice	0.819	0.320	**0.002**
Shading method*farming practice	0.344	0.187	0.761

According to September's results shown in Table 18, the experimental units applying the IC farming practice had a mean CBB infestation rate between 2%-12% which, statistically, is significantly higher than those applying the IO and LO farming practice.

Table 18: Results of Tukey's tests for multiple comparison intervals of the farming practices in September in relation to the mean *Hypothenemus hampei* infestation rate (%). P-values below 5% are statistically significant and indicated in bold.

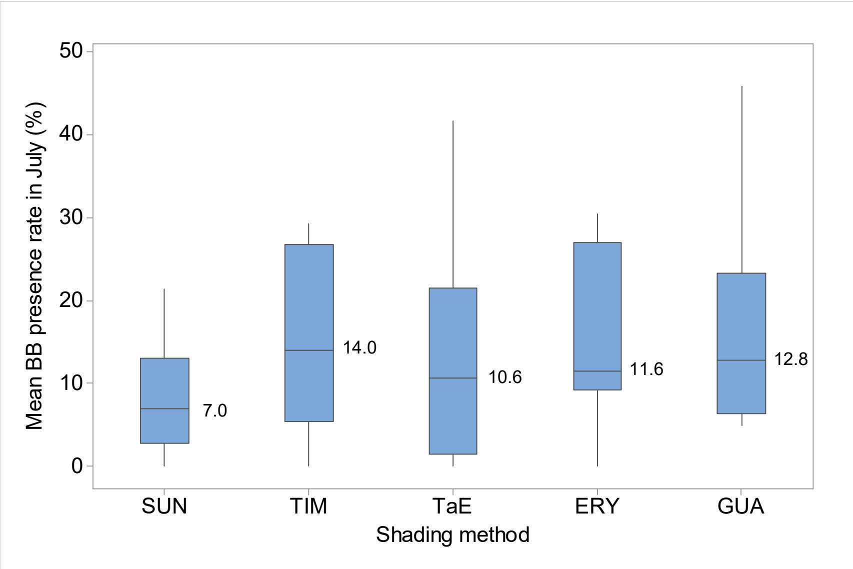
September		
Farming practice		
Difference between mean rates	*95% confidence intervals (mean CBB infestation rate difference in %)*	*Adjusted p-value*
IC-MC	(-0.06; 9.67)	0.054
IC-IO	(1.79; 11.52)	**0.004**
IC-LO	(1.73; 11.46)	**0.004**
MC-IO	(-3.01; 6.72)	0.737
MC-LO	(-3.07; 6.66)	0.755
IO-LO	(-4.92; 4.81)	1

6.3 *Beauveria bassiana* presence

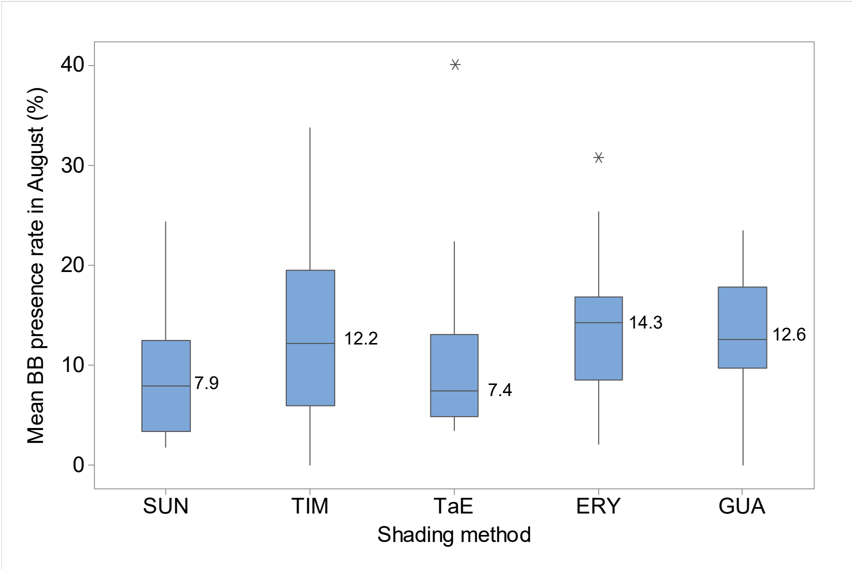
Figure 17 shows that the median BB presence rate found in the SUN shading method in July and August is lower than the one found in the other shading methods, except for the TaE shading method in August. Further, the median BB presence rate found in the TaE shading method in August and September is lower than the one found in the other shading methods. With regard to the histogram, the mean BB presence rate in the SUN shading method is the lowest in each month assessed.

Figure 17. Graphics of the mean *Beauveria bassiana* presence rate in relation to the shading method: A-C: Box and whisker plots of the mean *Beauveria bassiana* presence rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Beauveria bassiana* presence rate (%) in relation to the shading method in July, August and September 2018

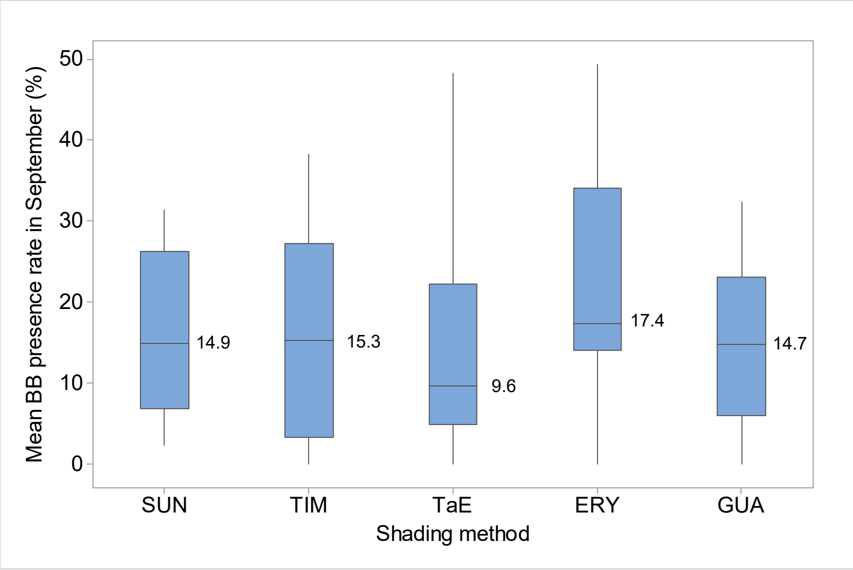
A



B



C



D

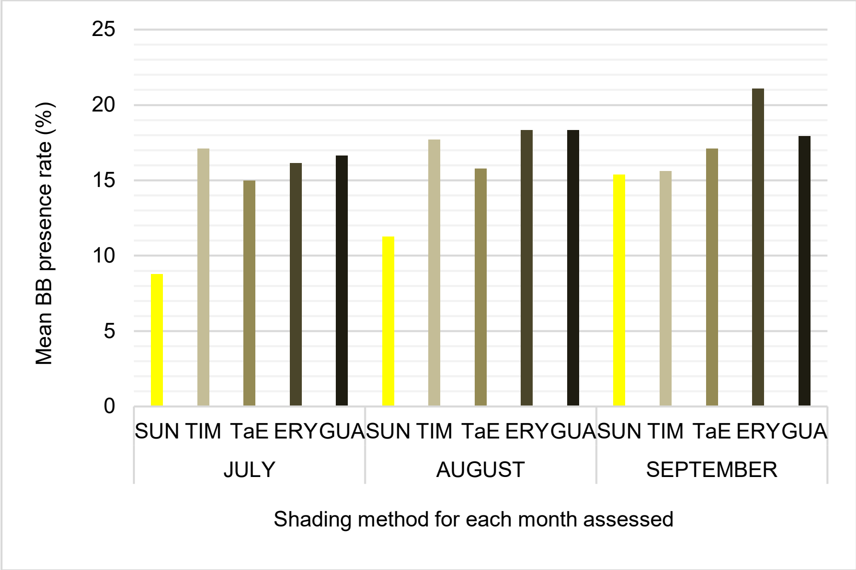
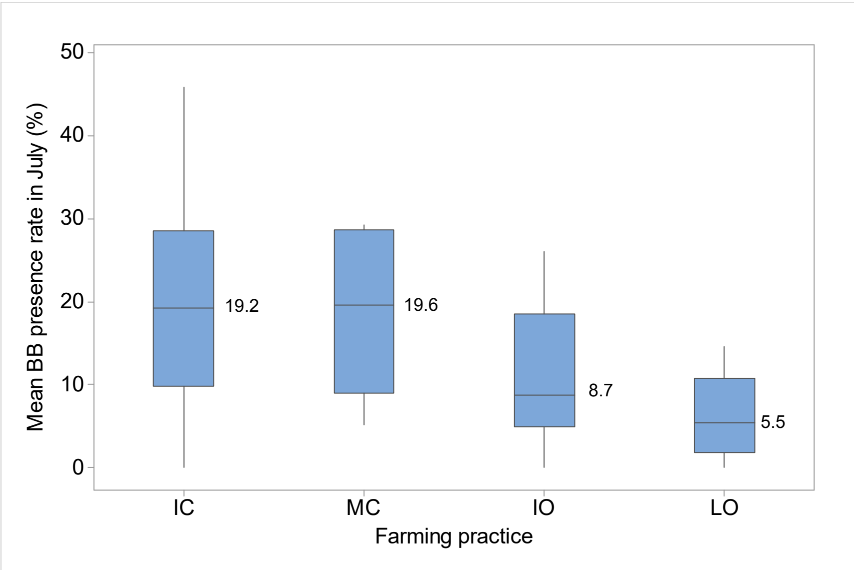


Figure 18 indicates that the LO and IO farming practices present a markedly lower BB presence rate than the IC and MC farming practices for both July and September. With regard to the histogram, the mean BB presence rate in the IC farming practice appears to be higher than in the other farming practices.

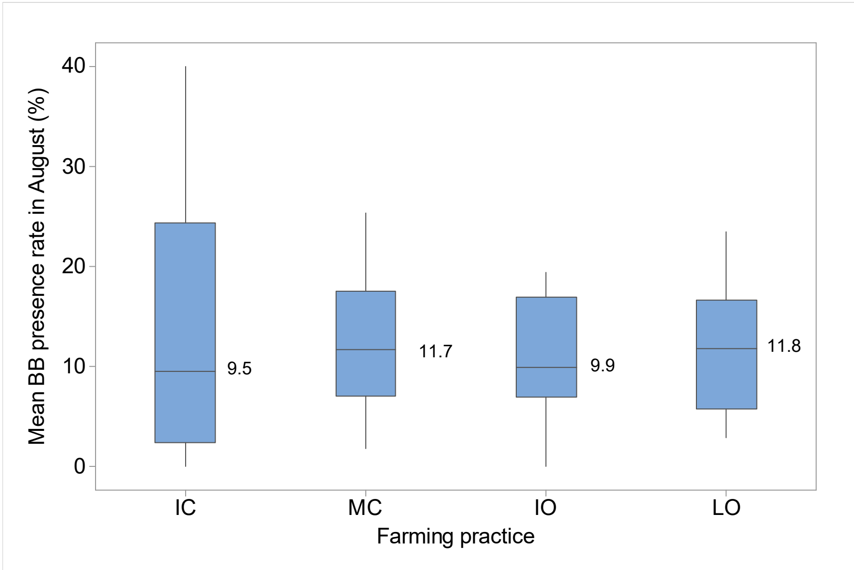
Figure 18. Graphics of the mean *Beauveria bassiana* presence rate in relation to the farming practice:

A-C: Box and whisker plots of the mean *Beauveria bassiana* presence rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: histogram of the mean *Beauveria bassiana* presence rate (%) in relation to the farming practice in July, August and September 2018

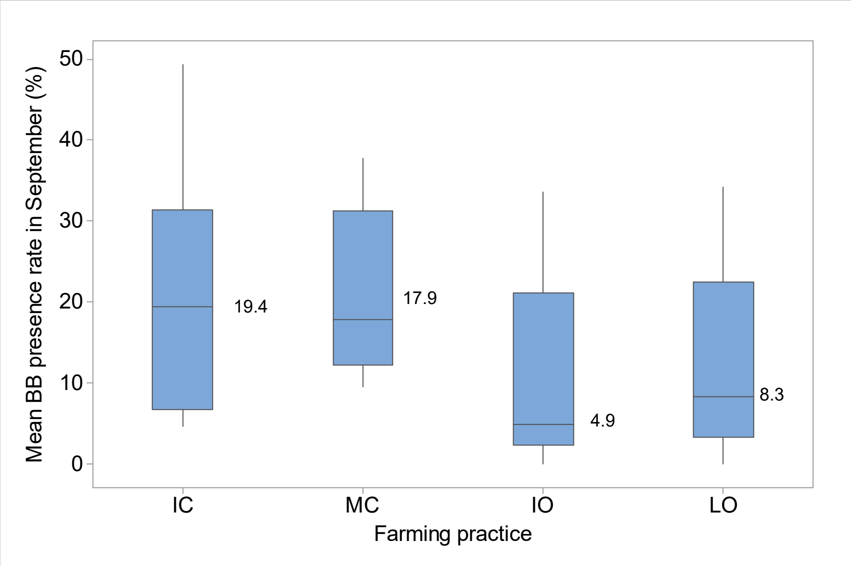
A



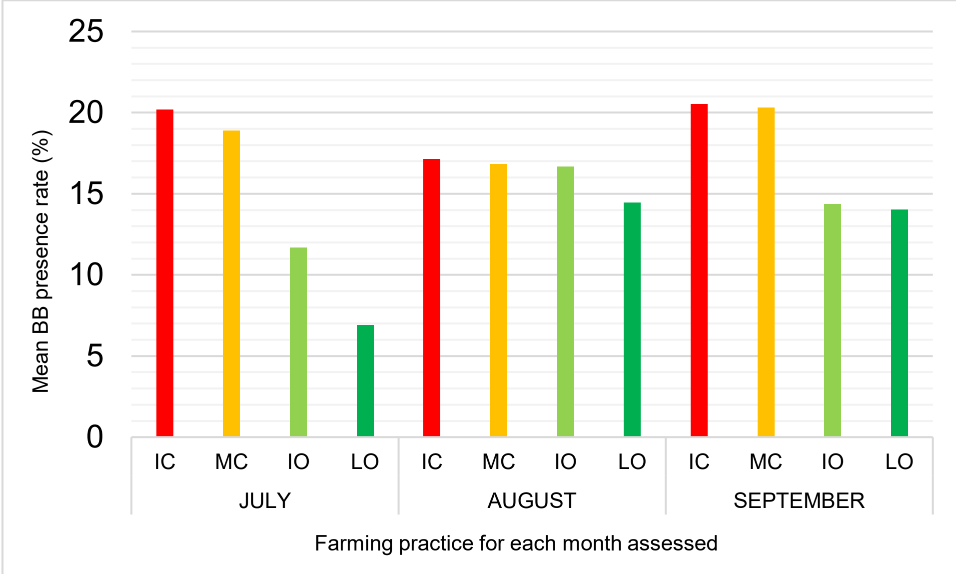
B



C



D

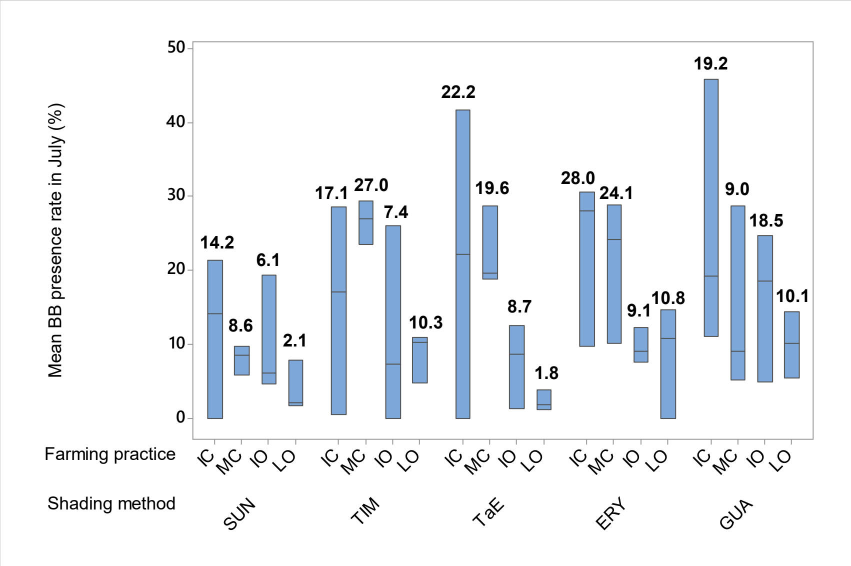


In Figure 19, the graphs show that the worst AFS systems with respect to BB infestation in July, August and September are as follows: TaE-LO with a median 1.8%, SUN-MC with a median 4.8% and TaE-IO with a median 2.2%. The best AFS systems are respectively: ERY-IC with a median 28%, TIM-IC with a median 19.6% and TaE-MC with a median 23.7%. Further, the histogram denotes that the mean BB presence rate is lower in IO and LO farming practices for all months assessed.

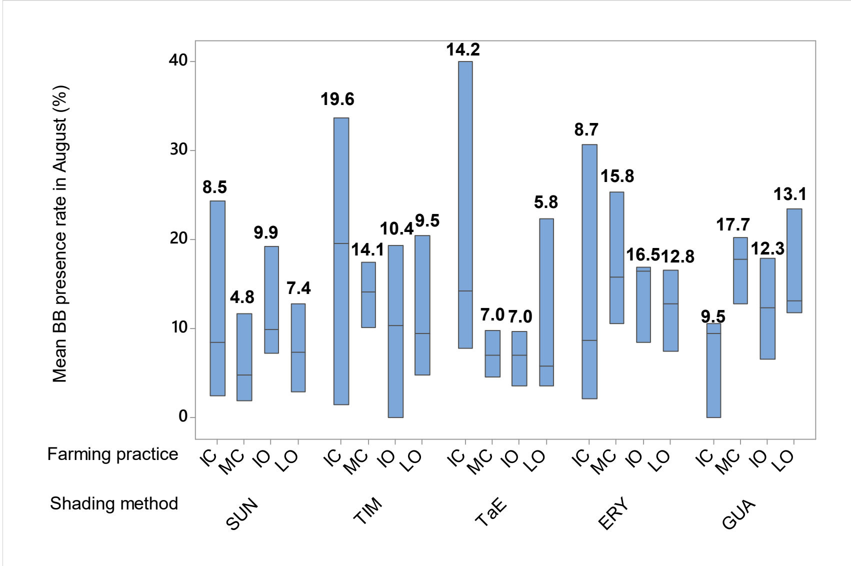
Figure 19. Graphics of the mean *Beauveria bassiana* presence rate in relation to agroforestry systems:

A-C: Box and whisker plots of the mean *Beauveria bassiana* presence rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Beauveria bassiana* presence rate (%) in relation to agroforestry systems in July, August and September 2018

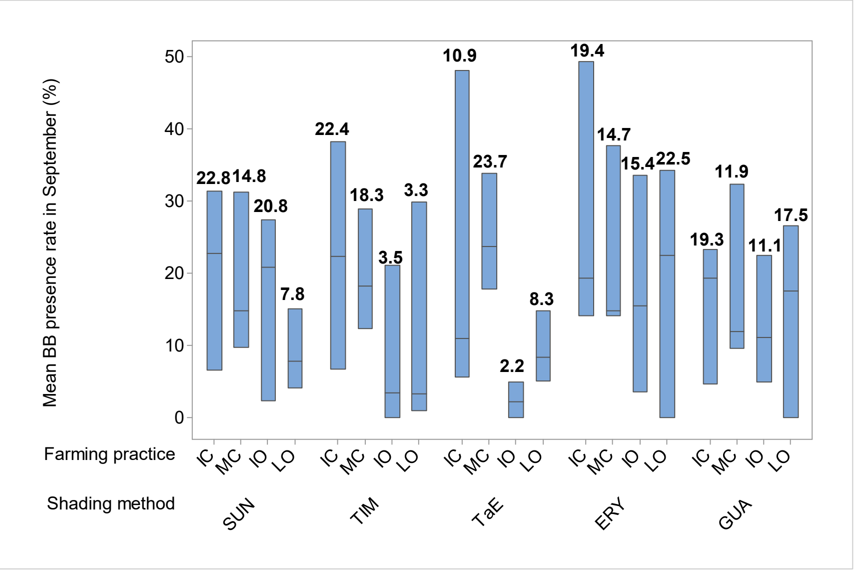
A



B



C



Mean BB presence rate in September (%)
50
40
30
20
10
0
22.8
14.8
20.8
7.8
22.4
18.3
3.5
3.3
10.9
23.7
2.2
8.3
19.4
14.7
15.4
22.5
19.3
11.9
11.1
17.5
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

D

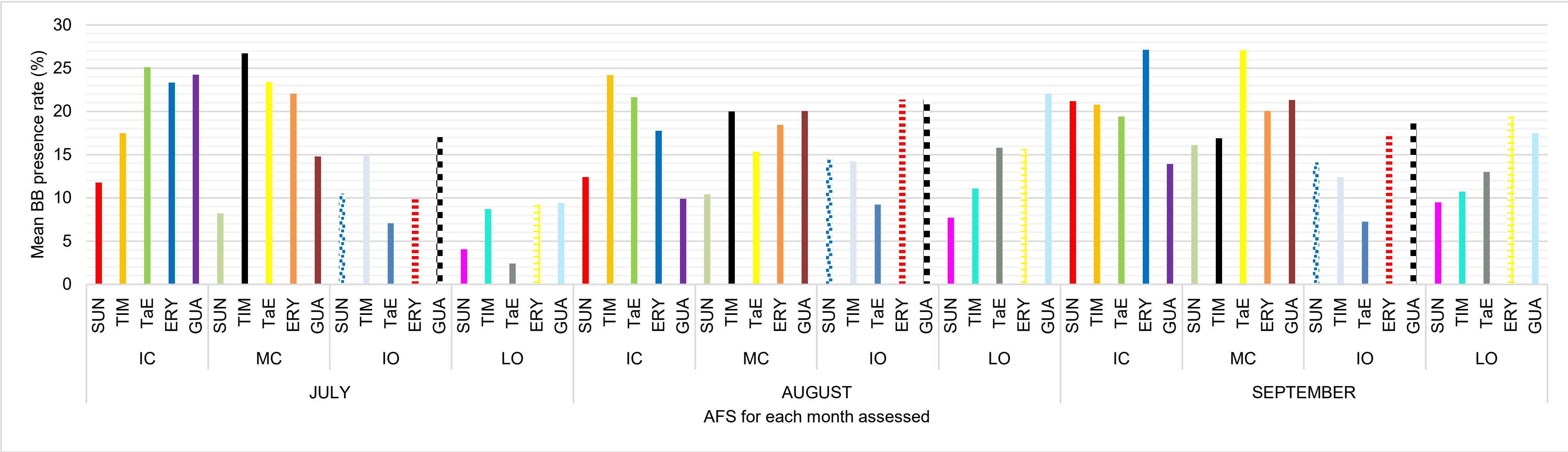


Table 19 shows that the the farming practice significantly impacts the mean BB presence rate in July (p-value= 0.9%) and September (p-value= < 0.1%).

Table 19: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Beauveria bassiana* presence rate (%). P-values below 5% are statistically significant and indicated in bold.

	p-value		
	July	August	September
Shading method	0.231	0.535	0.159
Farming practice	**0.009**	0.676	**< 0.001**
Shading method*farming practice	0.688	0.417	0.486

According to July's results shown in Table 20, the experimental units applying an MC farming practice had a mean BB presence rate statistically and significantly between 1.3 and 6.6 times higher than those applying an LO farming practice. In September the experimental units applying an IC farming practice had a mean

BB presence rate statistically and significantly between 3% and 17% higher than those applying an IO farming practice, and statistically and significantly between 2% and 16% higher than those applying an LO farming practice. In addition, the experimental units applying an MC farming practice showed a mean BB presence rate statistically and significantly between 2% and 16% higher than those applying an IO farming practice and statistically and significantly between 1% and 15% higher than those applying an LO farming practice.

Table 20: Results of Tukey's tests for multiple comparison intervals of the farming practices in July and September in relation to the mean *Beauveria bassiana* presence rate (%). P-values below 5% are statistically significant and indicated in bold.

July		
Farming practice		
Difference between mean rates	*95% confidence intervals (mean BB presence rate difference in % with the log transformation)*	*Adjusted p-value*
IC-MC	(-0.487; 0.228)	0.765
IC-IO	(-0.211; 0.504)	0.691
IC-LO	(-0.027; 0.688)	0.078
MC-IO	(-0.082; 0.633)	0.18
MC-LO	(0.103; 0.818)	**0.007**
IO-LO	(-0.173; 0.542)	0.515
September		
Farming practice		
Difference between mean rates	*95% confidence intervals (mean BB presence rate difference in %)*	*Adjusted p-value*
IC-MC	(-6.42; 8.02)	0.991
IC-IO	(2.75; 17.19)	**0.004**

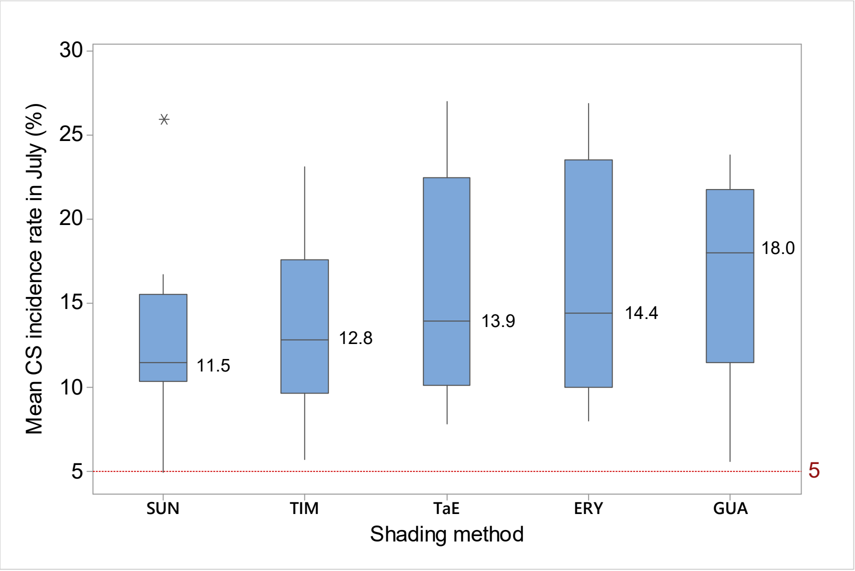
IC-LO	(1.63; 16.07)	**0.011**
MC-IO	(1.95; 16.39)	**0.008**
MC-LO	(0.83; 15.27)	**0.024**
IO-LO	(-8.34; 6.1)	0.975

6.4 *Colletotrichum spp*. incidence

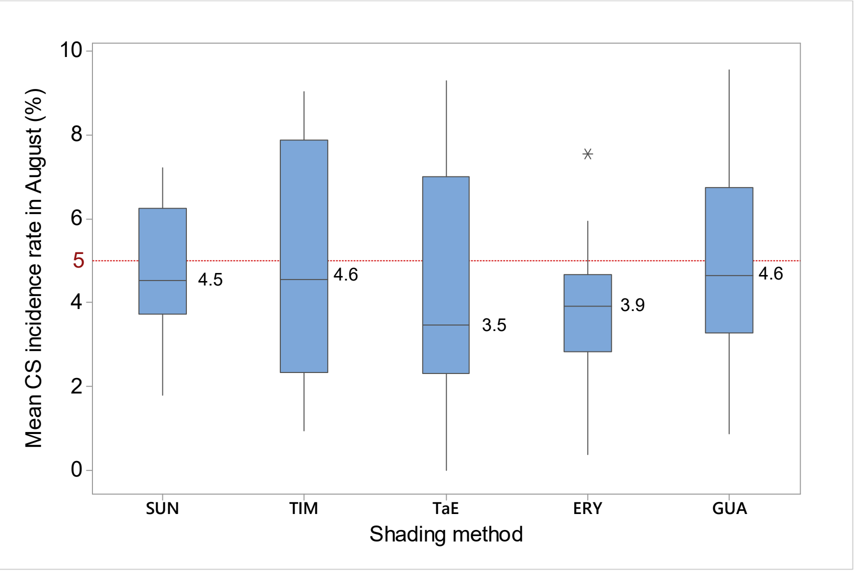
Figure 20 shows that in July the median CS incidence rate in the ERY and GUA shading methods was higher than that in the other shading methods. Further, the histogram indicates that for each month assessed the SUN shading method always had the lowest mean CS incidence rate. The histogram also shows that the mean CS incidence rate decreases during the months assessed. In September, the mean CS incidence rate was even below the economic threshold.

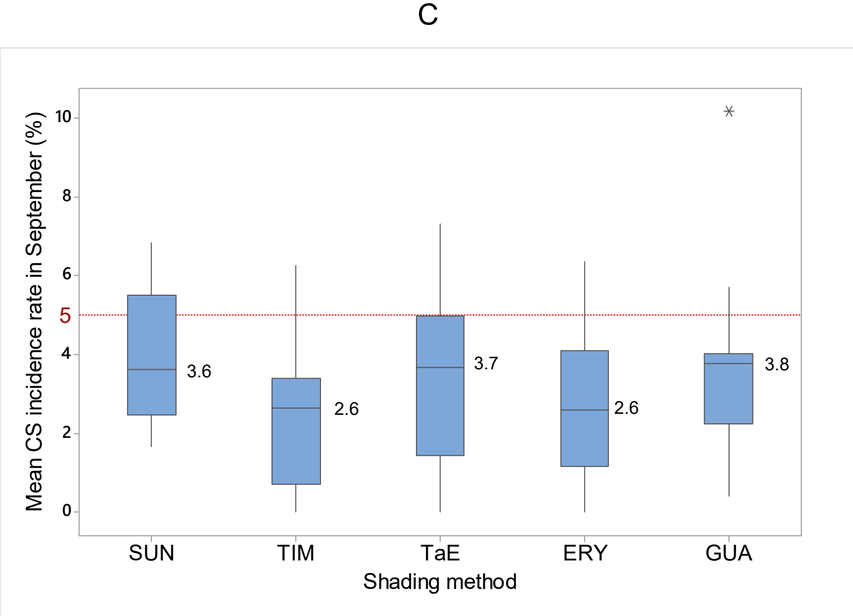
Figure 20. Graphics of the mean *Colletotrichum spp.* incidence rate in relation to the shading method: A-C: Box and whisker plots of the mean *Colletotrichum spp*. incidence rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Colletotrichum spp.* incidence rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

A



B





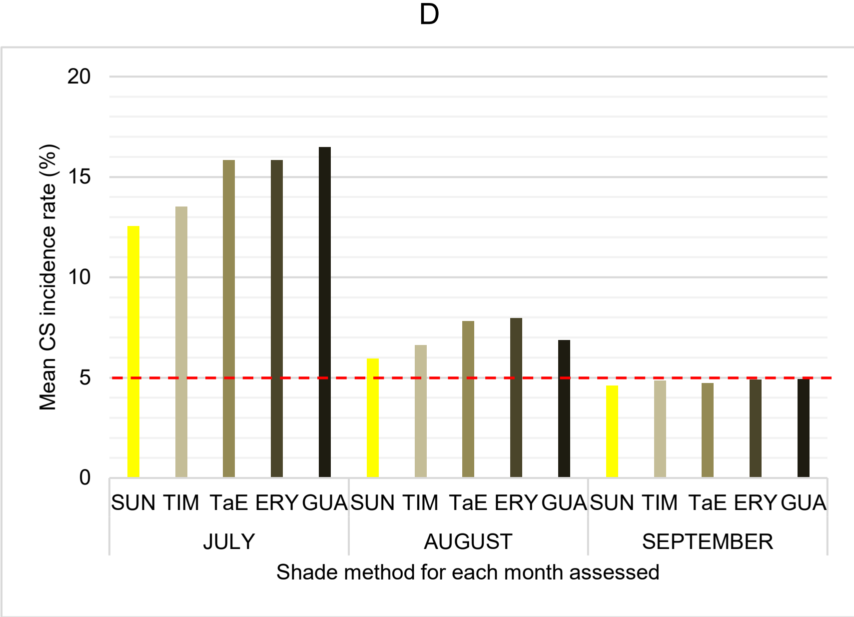
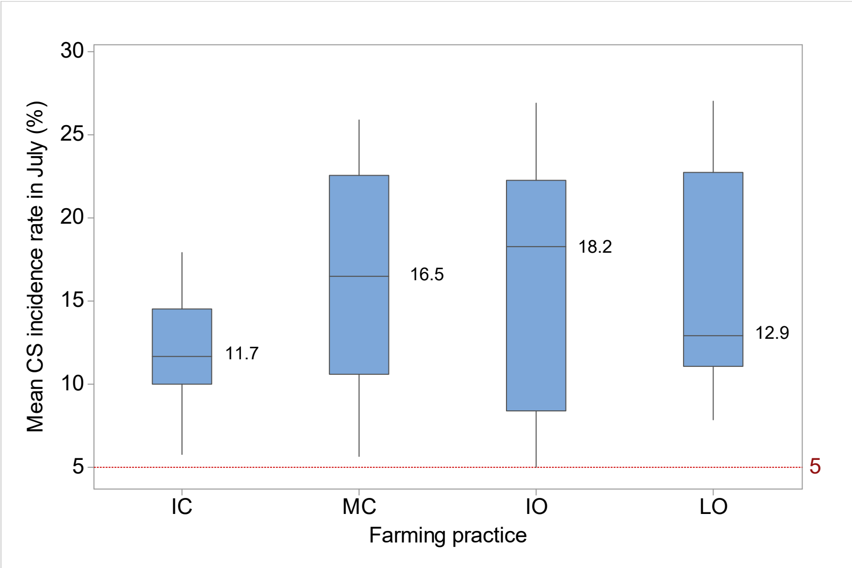


Figure 21 indicates that in July the MC and IO farming practices presented a higher CS incidence rate than that of the other farming practices. The histogram denotes a global continuous decrease of the mean CB incidence during the months assessed. In September, the mean CS incidence rate was even below the economic threshold.

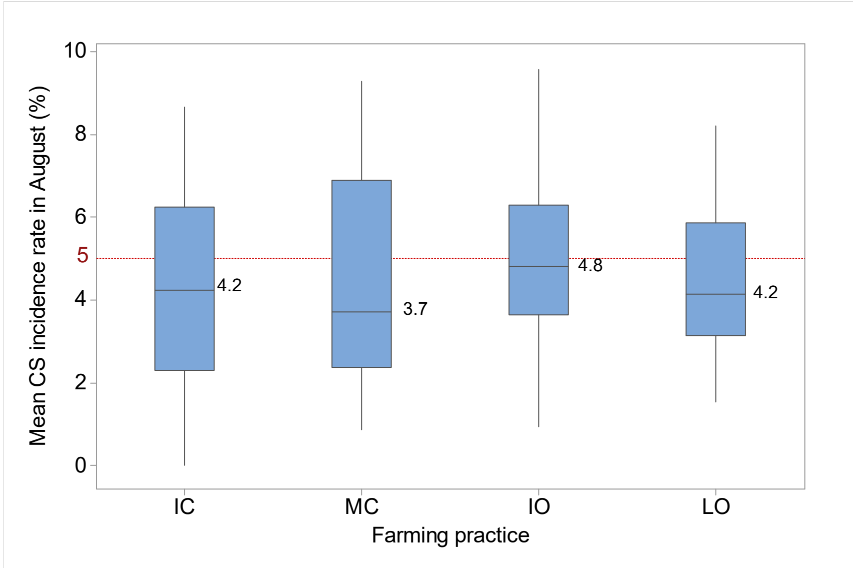
Figure 21. Graphics of the mean *Colletotrichum spp.* incidence rate in relation to the farming practice:

A-C: Box and whisker plots of the mean *Colletotrichum spp.* incidence rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Colletotrichum spp.* incidence rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

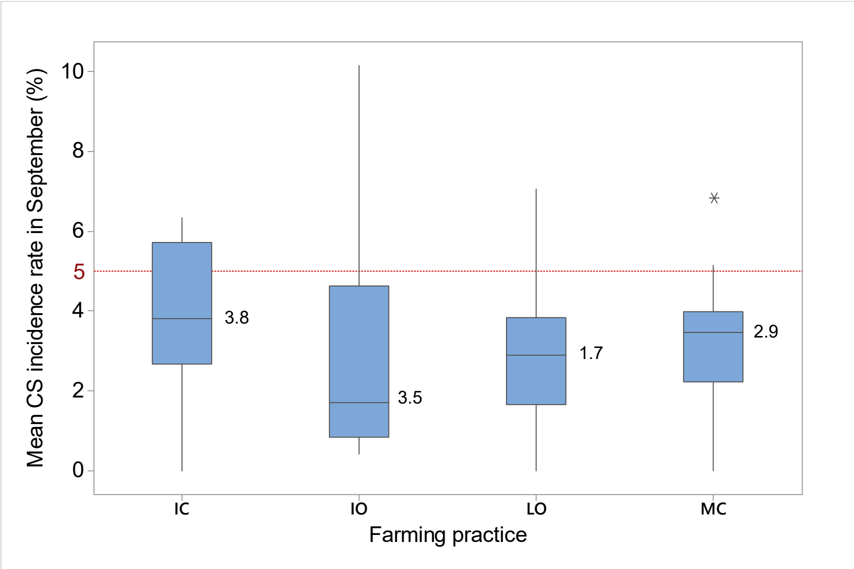
A



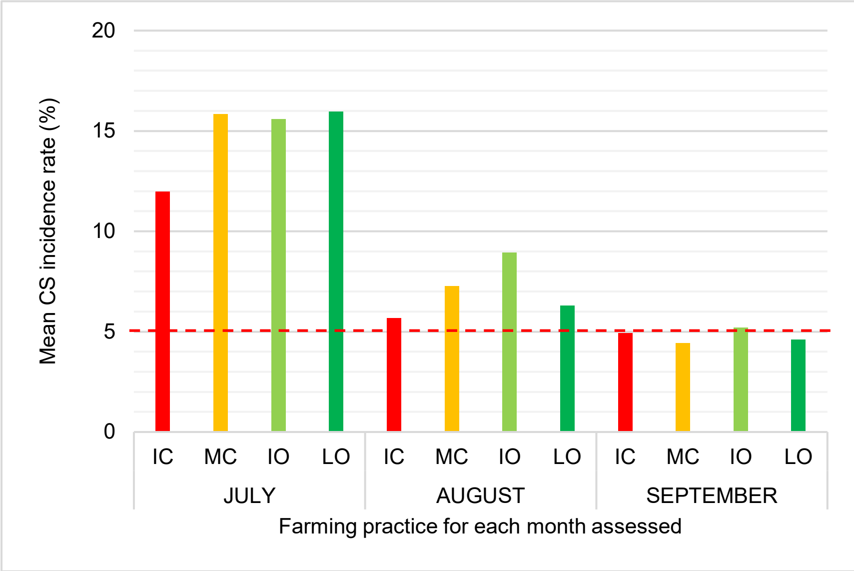
B



C



D

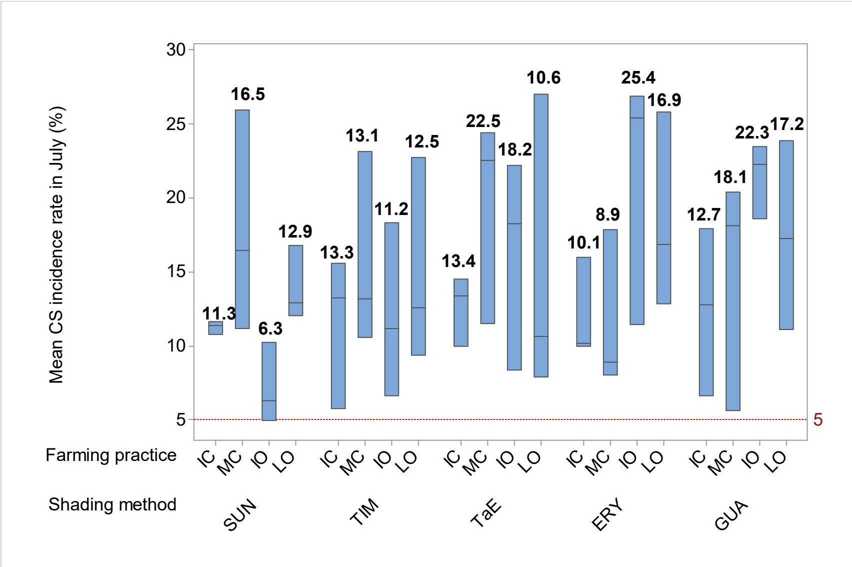


In Figure 22, the July, August and September graphs show that the worst AFS systems with respect to CB incidence are as follows: ERY-LO with a median 25.4%, TIM-LO with a median 6.9% and TaE-IO with a median 4.6%. The best AFS systems are as follows: SUN-IO with a median 6.3%, TIM-MC with a median 2.4% and TIM-IO with a median 0.8%. Further, the histogram denotes a global continuous decrease of CB incidence during the months assessed.

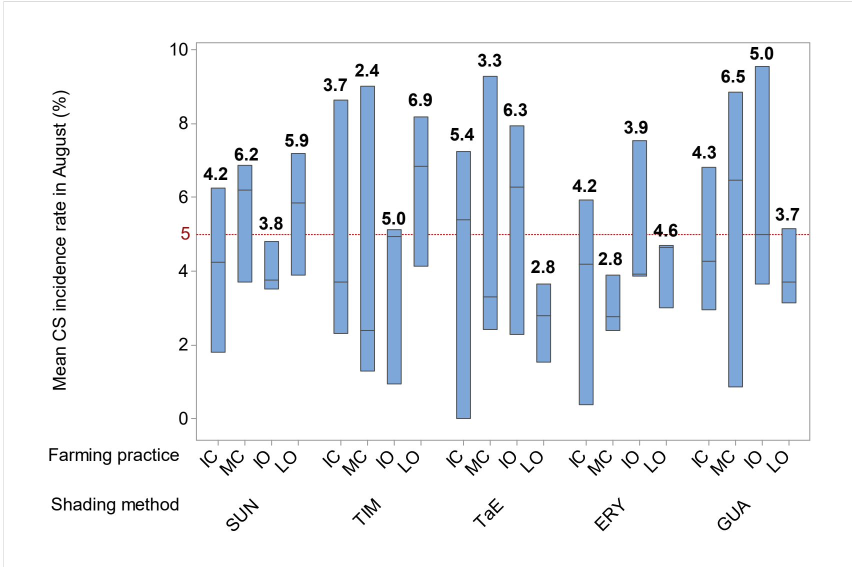
Figure 22. Graphics of the mean *Colletotrichum spp.* incidence rate in relation to agroforestry systems:

A-C: Box and whisker plots of the mean *Colletotrichum spp.* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Colletotrichum spp.* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

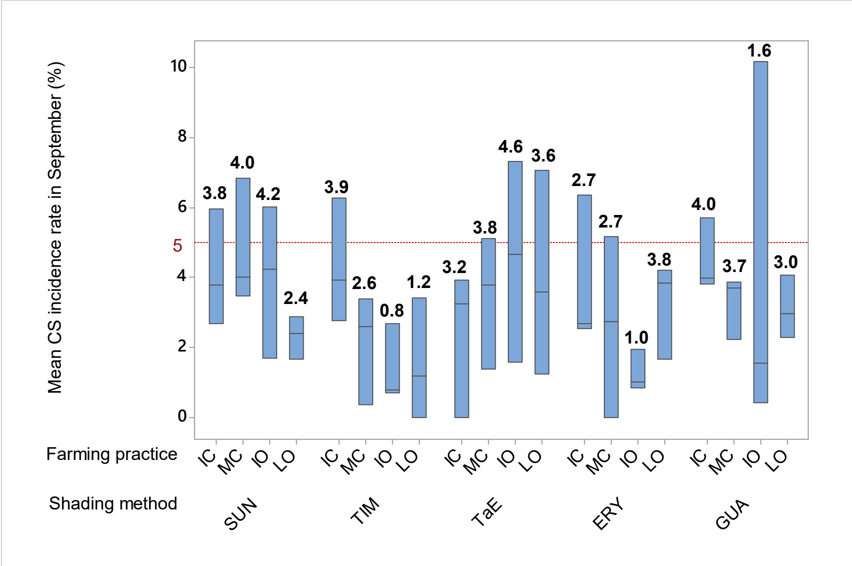
A



B



C



Mean CS incidence rate in September (%)
10
8
6
5
4
2
0
3.8
4.0
4.2
2.4
3.9
2.6
0.8
1.2
3.2
3.8
4.6
3.6
2.7
2.7
1.0
3.8
4.0
3.7
1.6
3.0
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

D

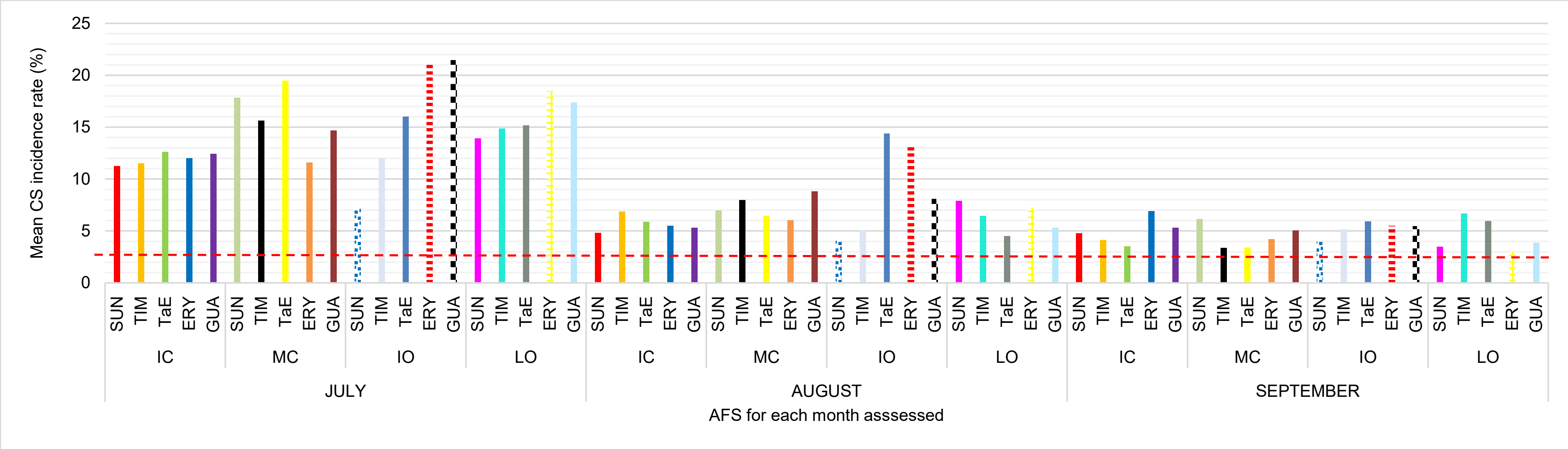


Table 21 shows that neither shading method nor farming practice had a statistically significant impact on the mean CS incidence rate, and further, there was no interaction between the two.

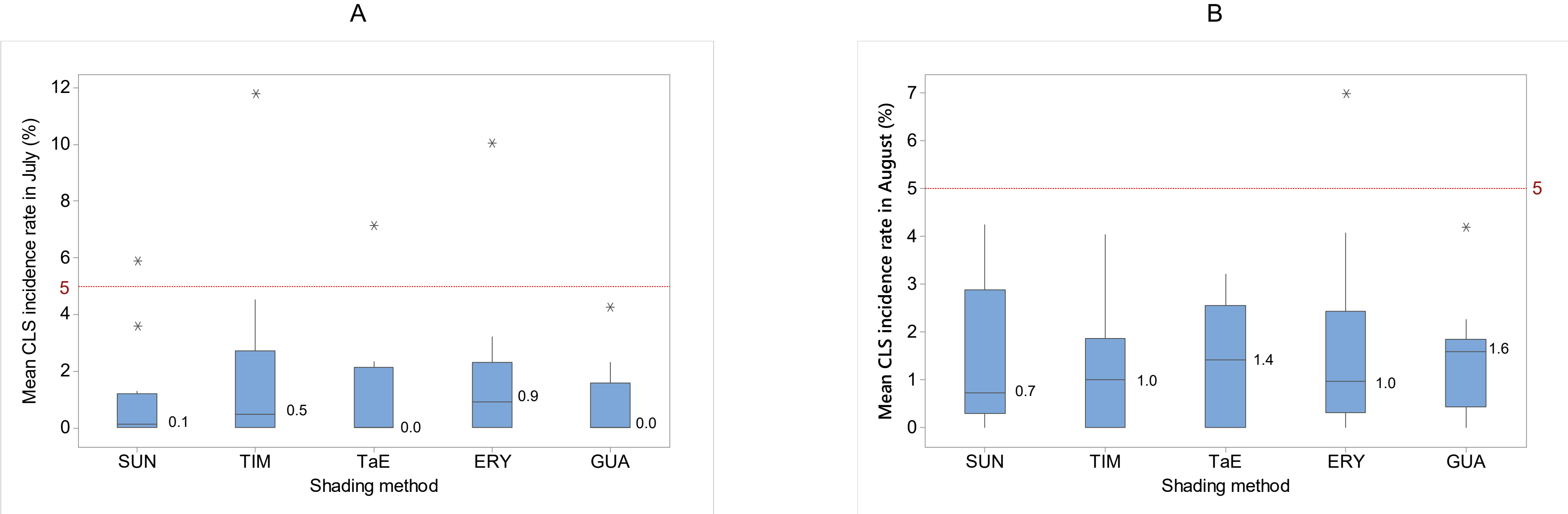
Table 21: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Colletotrichum spp.* incidence rate (%). P-values below 5% are statistically significant and indicated in bold.

	p-value		
	July	August	September
Shading method	0.59	0.823	0.143
Farming practice	0.269	0.933	0.4
Shading method*farming practice	0.325	0.834	0.325

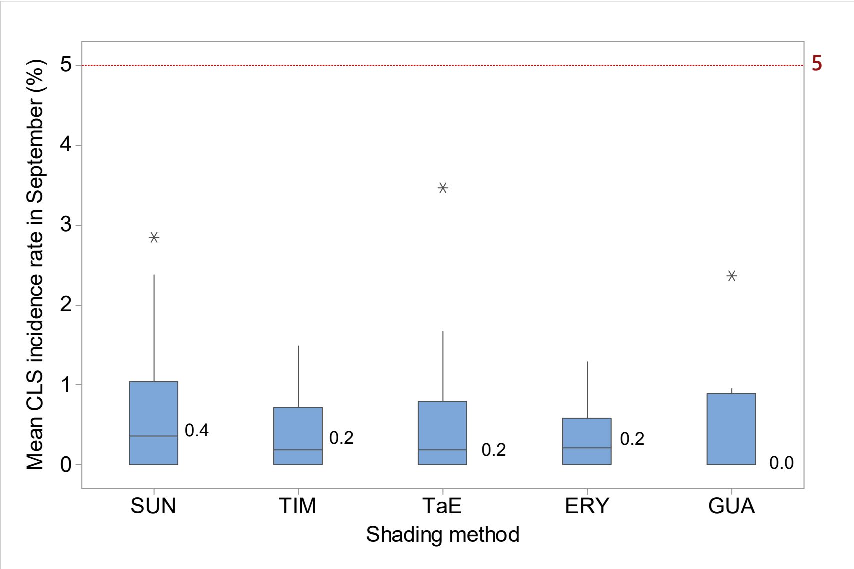
6.5 *Cercospora coffeicola* incidence

Figure 23 shows that the mean CLS incidence rate does not greatly differ from one shading method to another. The infestation was below the economic threshold during all the months assessed. However, the histogram denotes a higher mean CLS incidence rate in August, in comparison with the other months.

Figure 23. Graphics of the mean *Cercospora coffeicola* incidence rate in relation to the shading method: A-C: Box and whisker plots of the mean *Cercospora coffeicola* incidence rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Cercospora coffeicola* incidence rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.



C



D

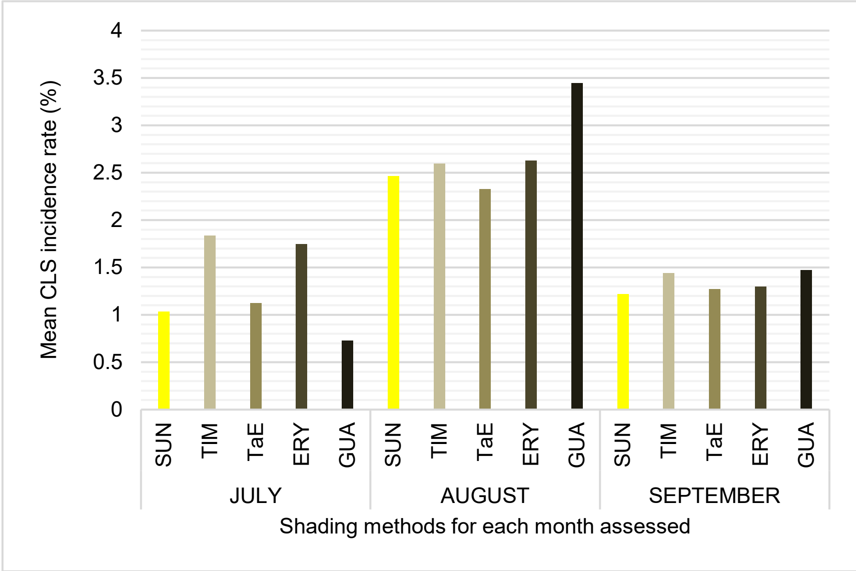
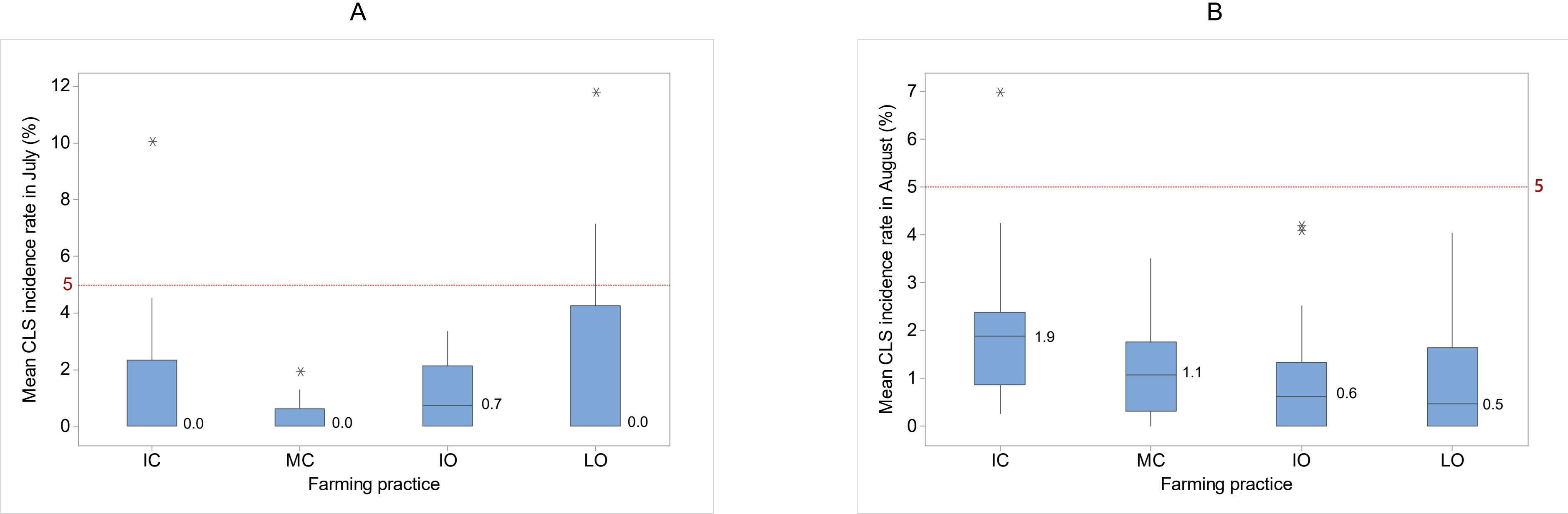


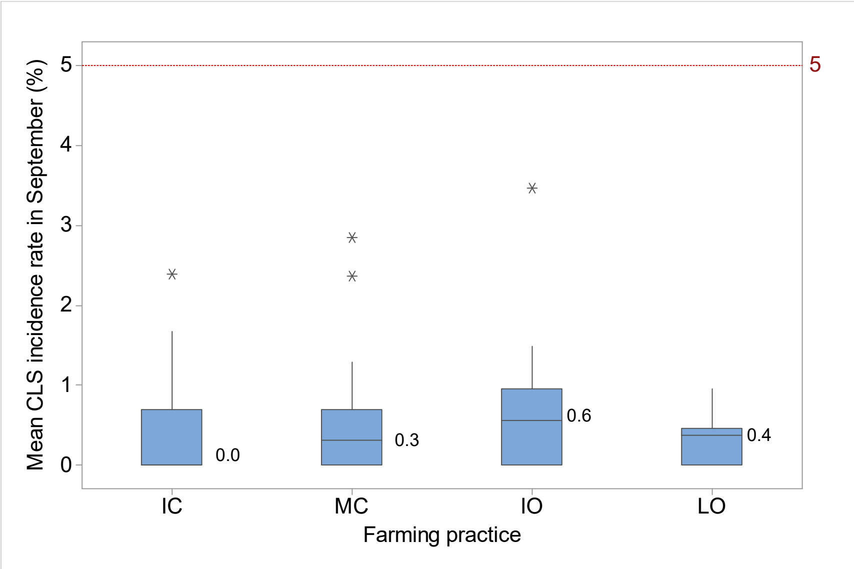
Figure 24 shows that the mean CLS incidence rate does not greatly differ from one farming practice to another. The infestation was below the economic threshold during all the months assessed. However, the histogram denotes a higher mean CLS incidence rate in August in comparison with the other months.

Figure 24. Graphics of the mean *Cercospora coffeicola* incidence rate in relation to the farming practice:

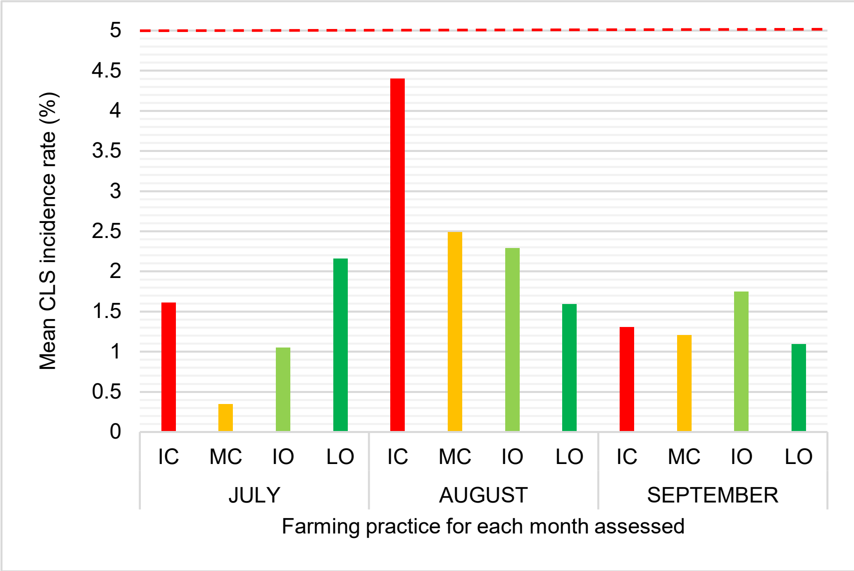
A-C: Box and whisker plots of the mean *Cercospora coffeicola* incidence rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Cercospora coffeicola* incidence rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.



C



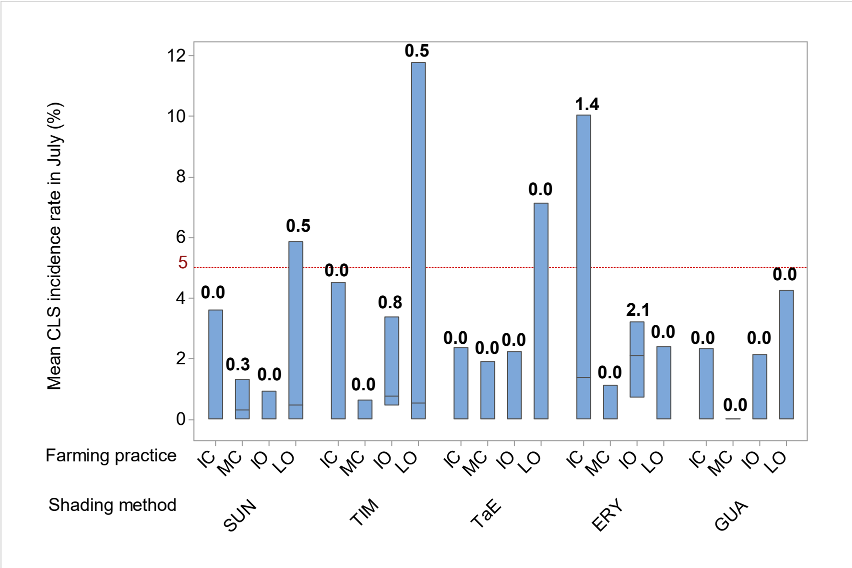
D



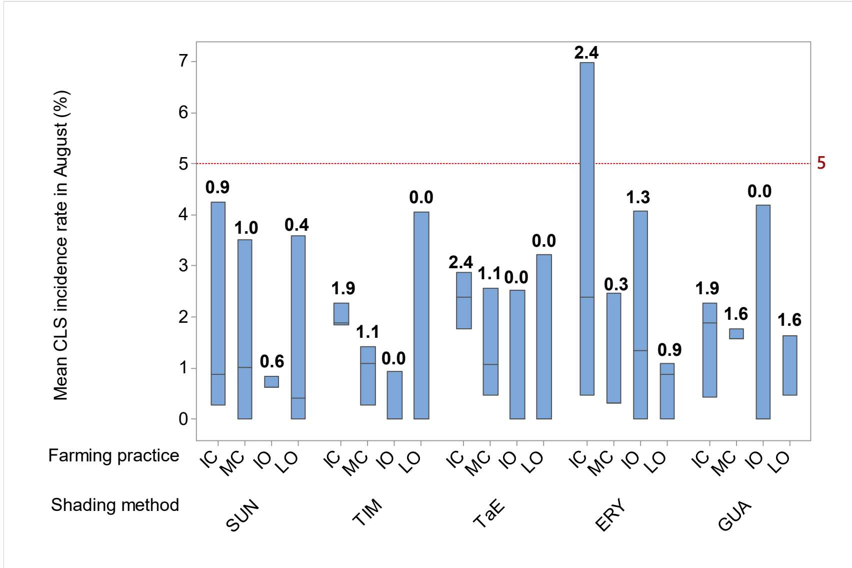
In Figure 25, the histogram shows that the mean CLS incidence rate is higher for the month of August in comparison with the other months. According to this histogram, except for TIM-IC AFS in August, all AFS present a mean CLS incidence rate below the economic threshold of 5%.

Figure 25. Graphics of the mean *Cercospora coffeicola* incidence rate in relation to agroforestry systems:
A-C: Box and whisker plots of the mean *Cercospora coffeicola* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Cercospora coffeicola* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

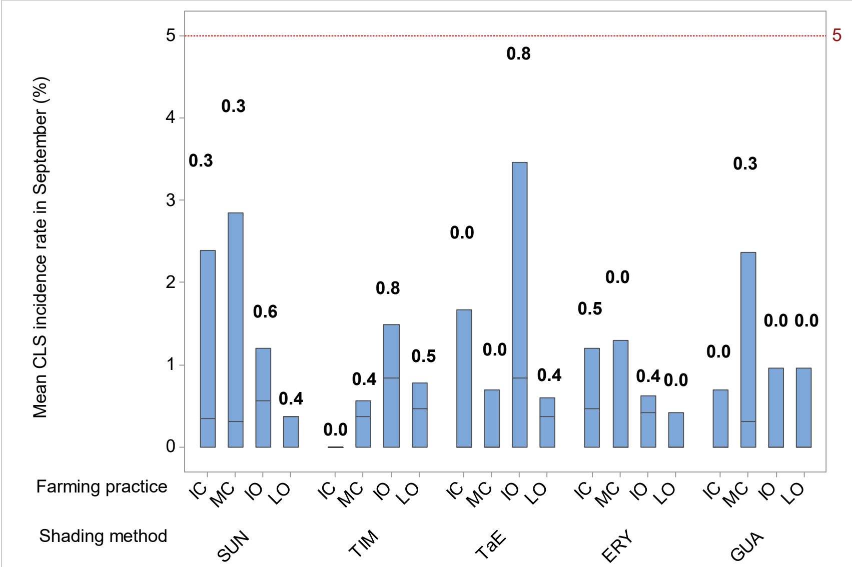
A



B



C



Mean CLS incidence rate in September (%)
0
1
2
3
4
5
5
0.3
0.3
0.6
0.4
0.0
0.4
0.8
0.5
0.0
0.0
0.8
0.4
0.5
0.0
0.4
0.0
0.0
0.3
0.0
0.0
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

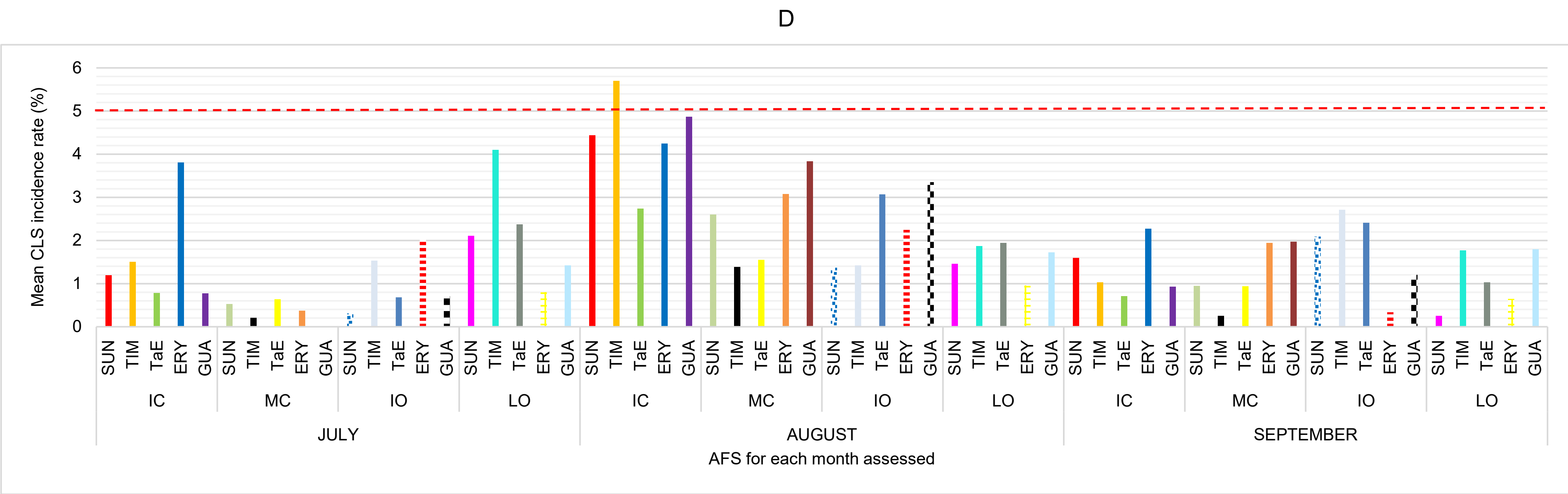


Table 22 shows that neither shading method nor farming practice had a statistically significant impact on the mean CS incidence rate, and further, there was no interaction between the two.

Table 22: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Cercospora coffeicola* incidence rate (%). P-values below 5% are statistically significant and indicated in bold.

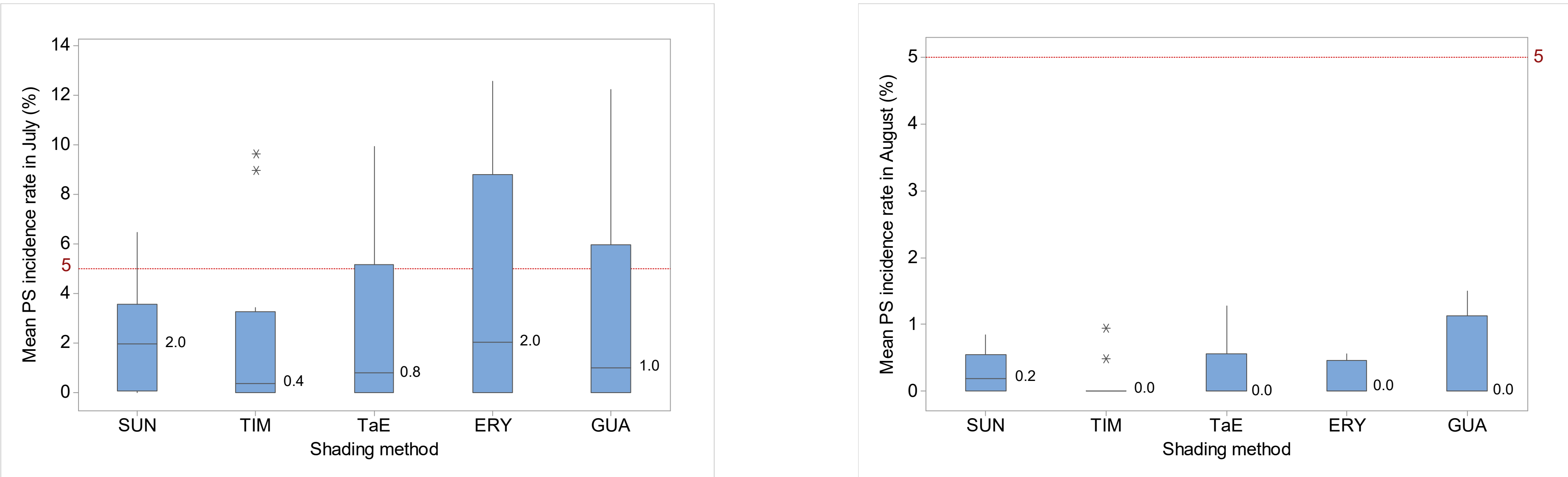
	p-value		
	July	August	September
Shading method	0.116	0.876	0.565
Farming practice	0.464	0.057	0.325
Shading method*farming practice	0.355	0.878	0.476

6.6 *Phoma spp*. incidence

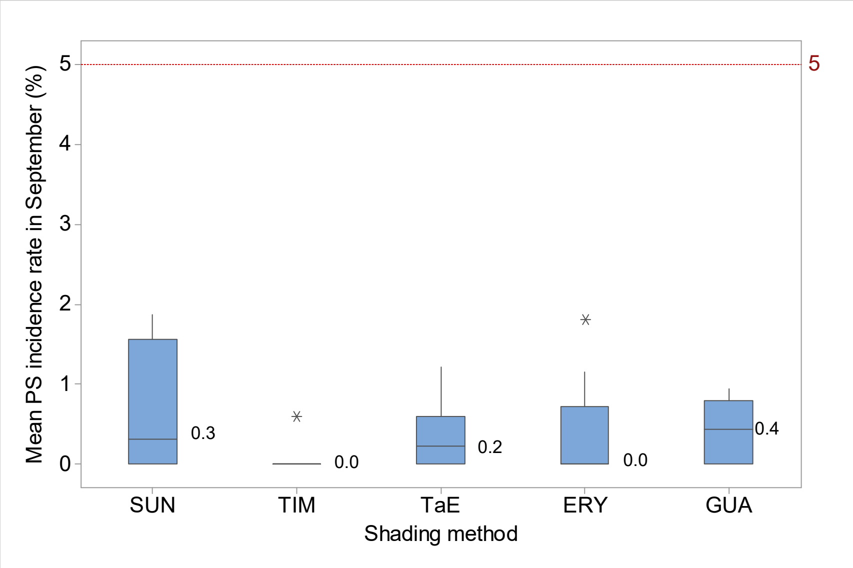
Regarding the box and whisker plots, Figure 26 shows that the mean PS incidence rate does not greatly differ from one shading method to another. The infestation was below the economic threshold during all months assessed. However, the histogram denotes that in July, August and September the two highest mean PS incidence rates assessed were found in the following shading methods: ERY and GUA, GUA and TIM, SUN and GUA. The histogram also shows mean PS incidence rates in July that were higher than in the other months.

Figure 26. Graphics of the mean *Phoma spp.* incidence rate in relation to the shading method: A-C: Box and whisker plots of the mean *Phoma spp.* incidence rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Phoma spp.* incidence rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

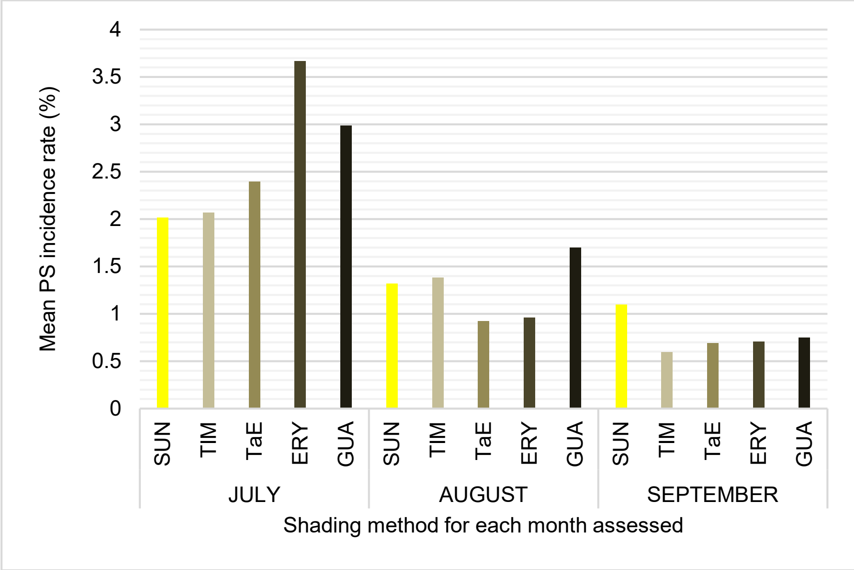
A B



C



D

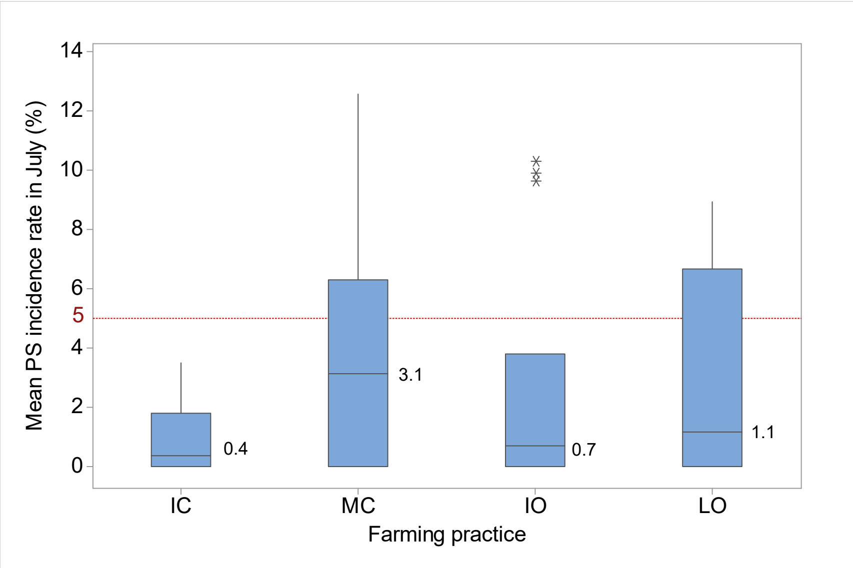


Regarding the box and whisker plots, Figure 27 shows that the mean PS incidence rate does not greatly differ from one shading method to another. The infestation was below the economic threshold for all months assessed. However, the histogram denotes that the mean PS incidence rate decreased during the months assessed, and that the two highest mean PS incidence rates assessed in July, August and September were found in the following farming practices: MC and LO, IO and LO, LO and IO.

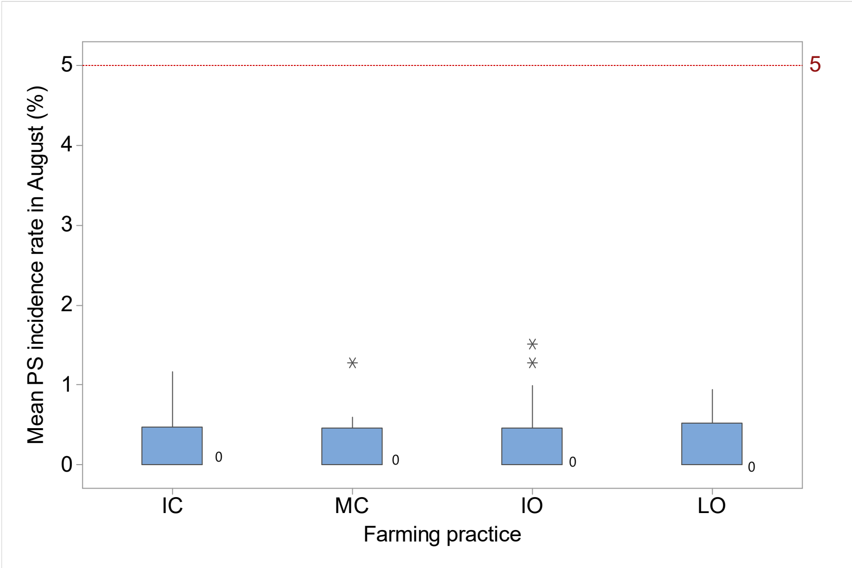
Figure 27. Graphics of the mean *Phoma spp.* incidence rate in relation to the farming practice:

A-C: Box and whisker plots of the mean *Phoma spp.* incidence rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Phoma spp.* incidence rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

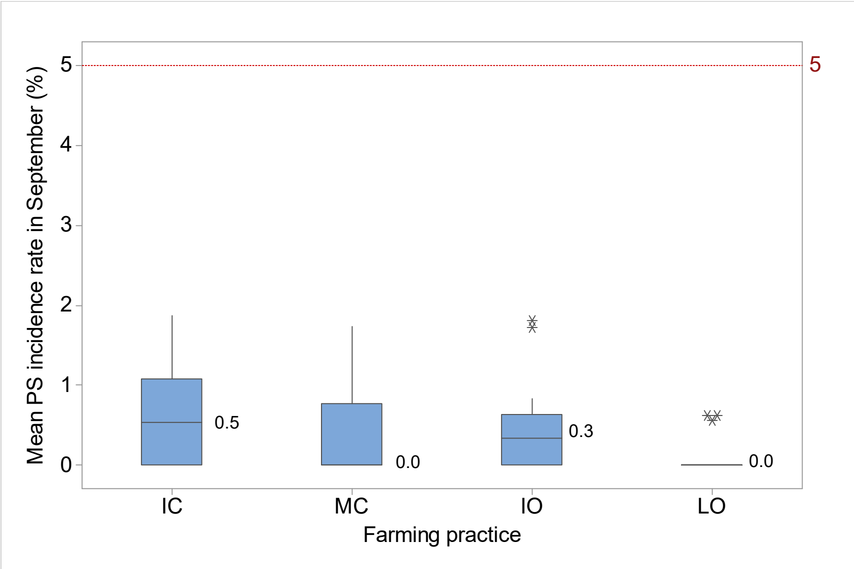
A



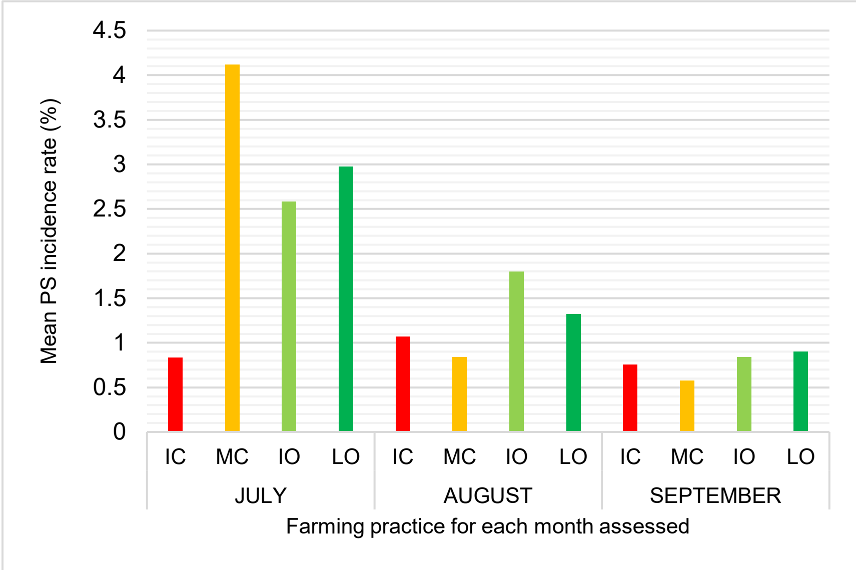
B



C



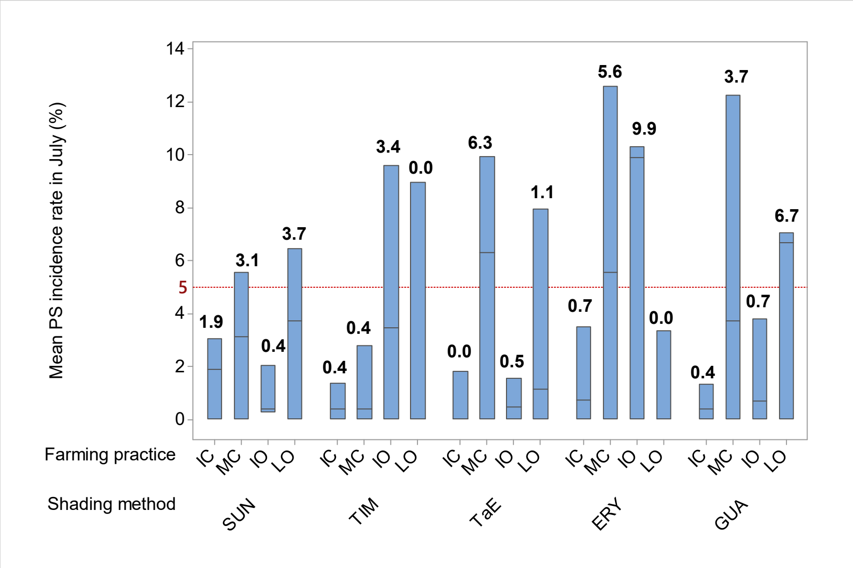
D



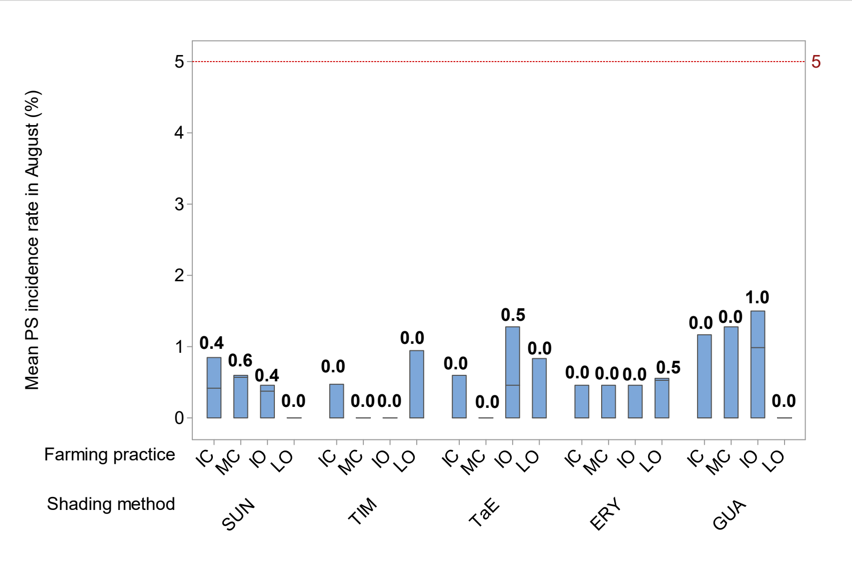
In Figure 28, the graph shows that in July the worst AFS with respect to PS incidence were: ERY-IO with a median 9.9%. The best AFS for the same month were: TIM-LO with a median 0%, TaE-IC with a median 0% and ERY-LO with a median 0%. For both August and September, there was no relevant difference between the AFS and median PS incidence rate. Regarding the histogram, it is interesting to point out that in July only, some mean results were above the economic threshold of 5% in the presence of the following AFS: TaE-MC, ERY-MC, GUA-MC and ERY-IO.

Figure 28. Graphics of the mean *Phoma spp.* incidence rate in relation to agroforestry systems:
A-C: Box and whisker plots of the mean *Phoma spp.* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Phoma spp.* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

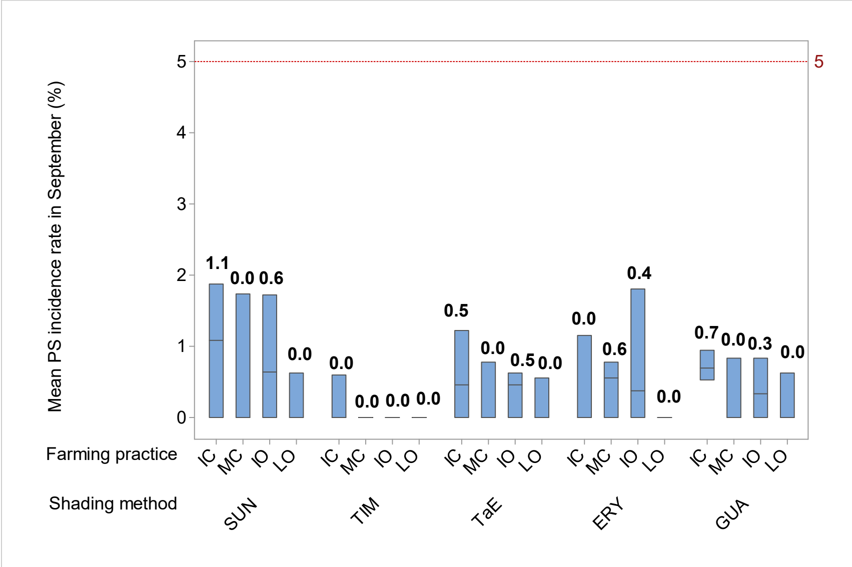
A



B



C


Mean PS incidence rate in September (%)
5
4
3
2
1
0
1.1
0.0
0.6
0.0
0.0
0.0
0.0
0.0
0.5
0.0
0.5
0.0
0.0
0.6
0.4
0.0
0.7
0.0
0.3
0.0
Farming practice
IC
MC
IO
LO
Shading method
SUN
TIM
TaE
ERY
GUA

D

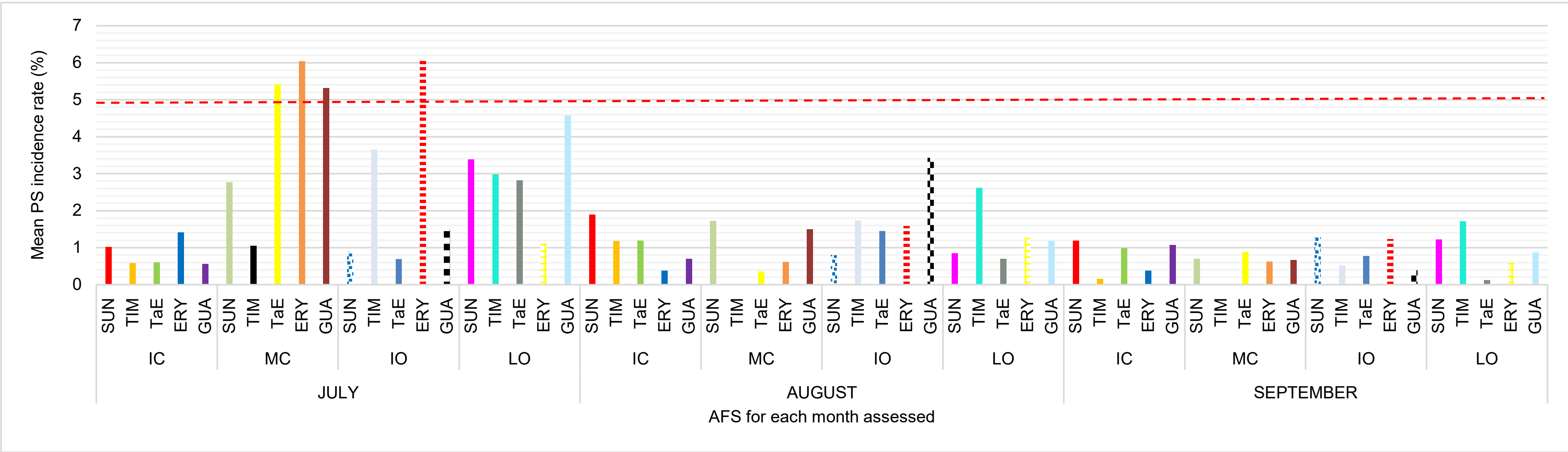


Table 23 shows that neither shading method nor farming practice had a statistically significant impact on the mean PS incidence rate, and further, there was no interaction between the two.

Table 23: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Phoma spp.* incidence rate (%). P-values below 5% are statistically significant and indicated in bold.

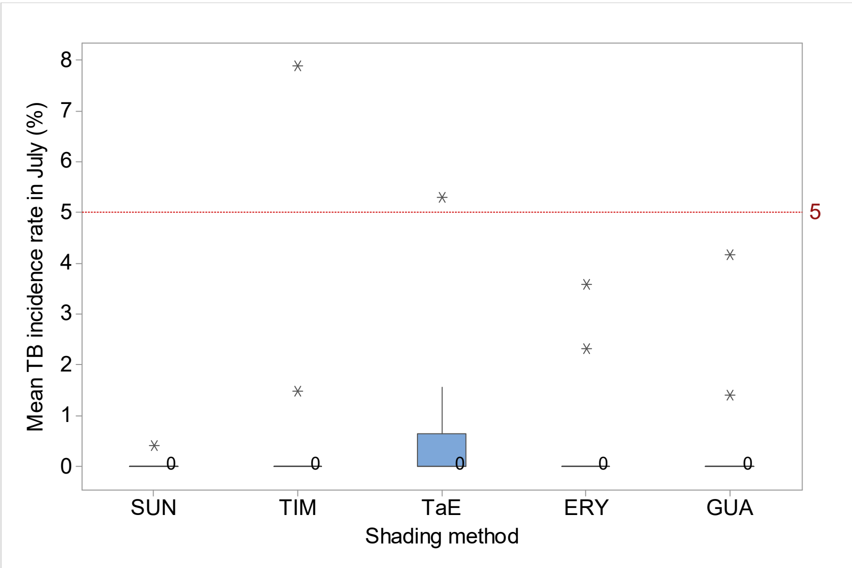
	p-value		
	July	August	September
Shading method	0.206	0.346	0.325
Farming practice	0.250	0.245	0.308
Shading method*farming practice	0.113	0.300	0.949

6.7 *Pellicularia koleroga* incidence

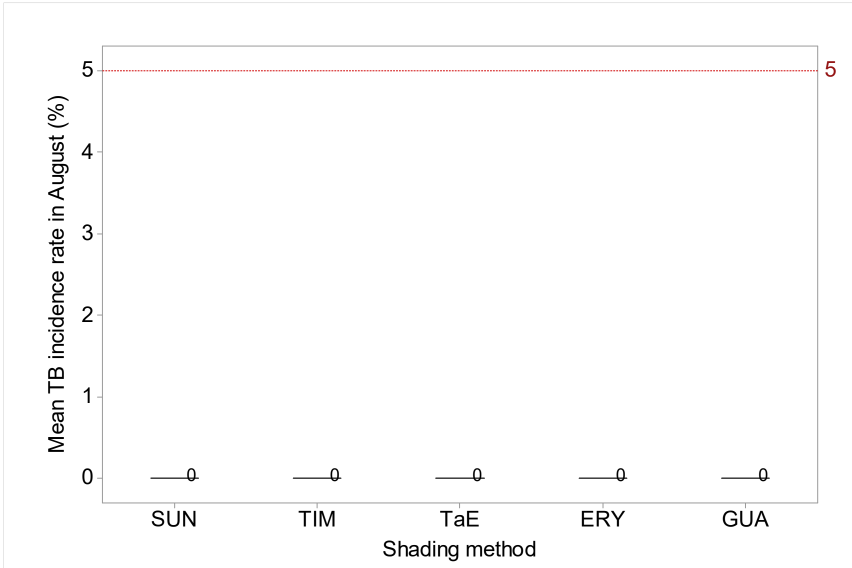
The graphs in Figure 29 show that the mean TB incidence rate does not differ from one shading method to another. The infestation was below the economic threshold for all the months assessed and almost nil.

Figure 29. Graphics of the mean *Pellicularia koleroga* incidence rate in relation to the shading method:
A-C: Box and whisker plots of the mean *Pellicularia koleroga* incidence rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Pellicularia koleroga* incidence rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

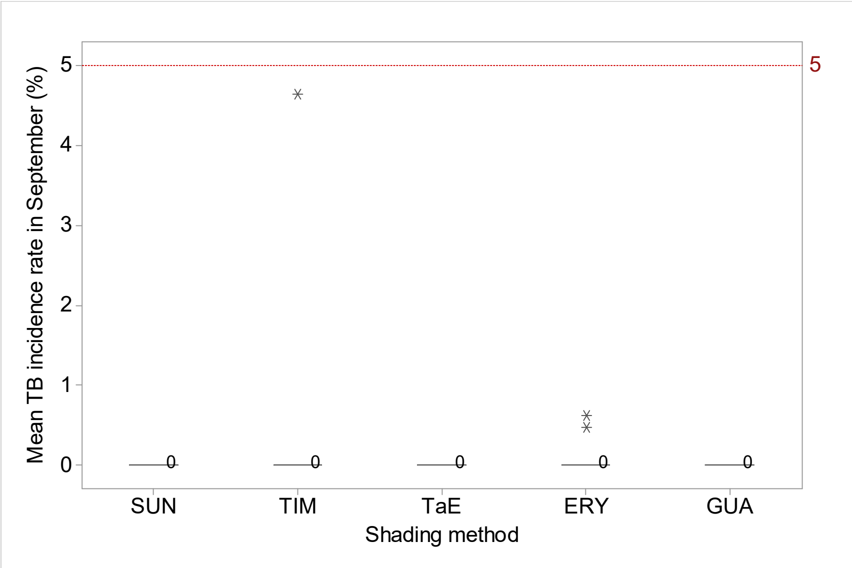
A



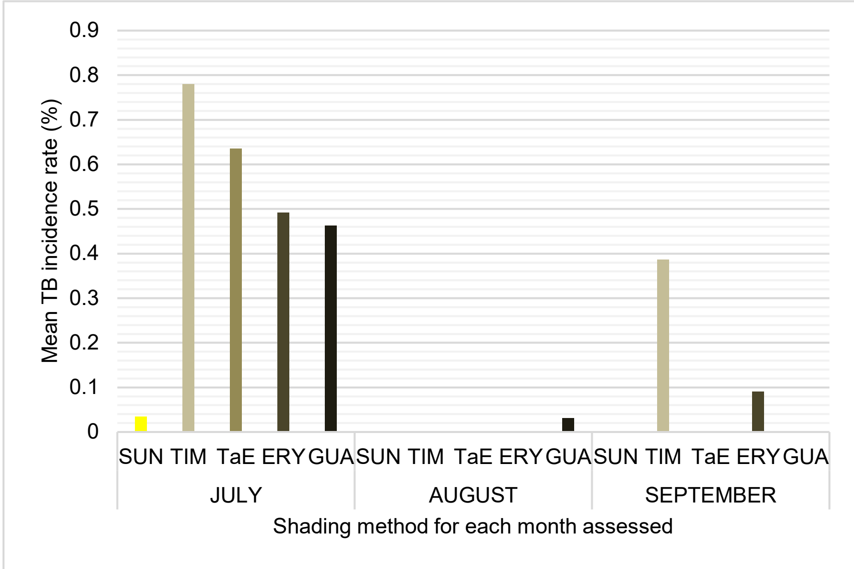
B



C



D

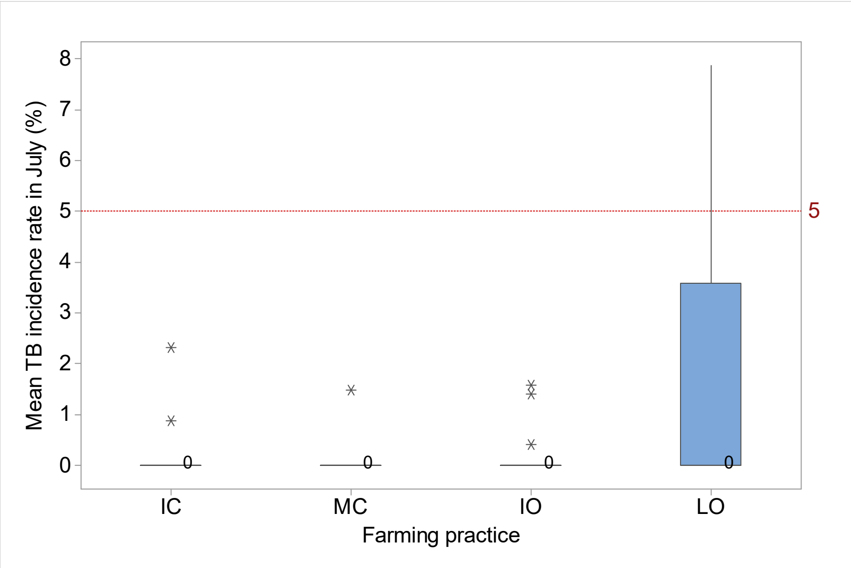


The graphs in Figure 30 show that the mean TB incidence rate did not differ from one farming practice to another. The infestation was below the economic threshold for all months assessed and almost nil.

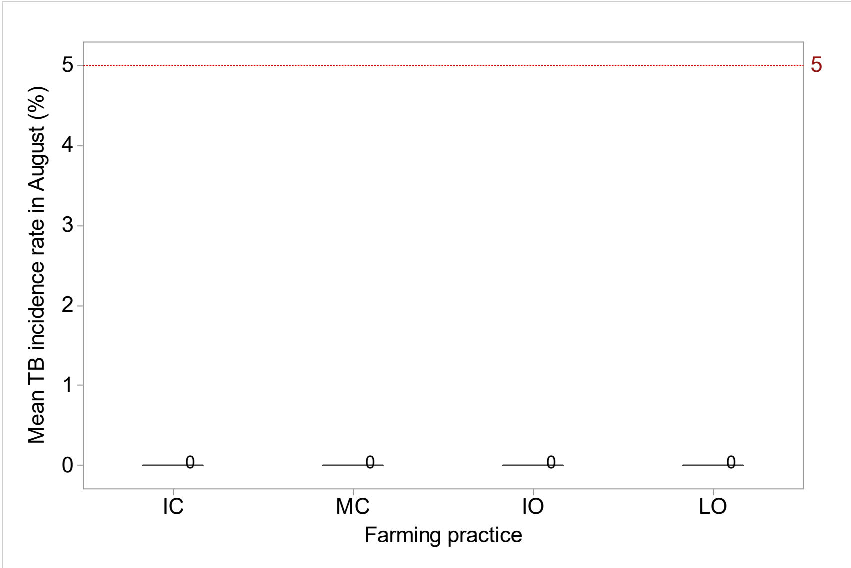
Figure 30. Graphics of the mean *Pellicularia koleroga* incidence rate in relation to the farming practice:

A-C: Box and whisker plots of the mean *Pellicularia koleroga* incidence rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Pellicularia koleroga* incidence rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

A

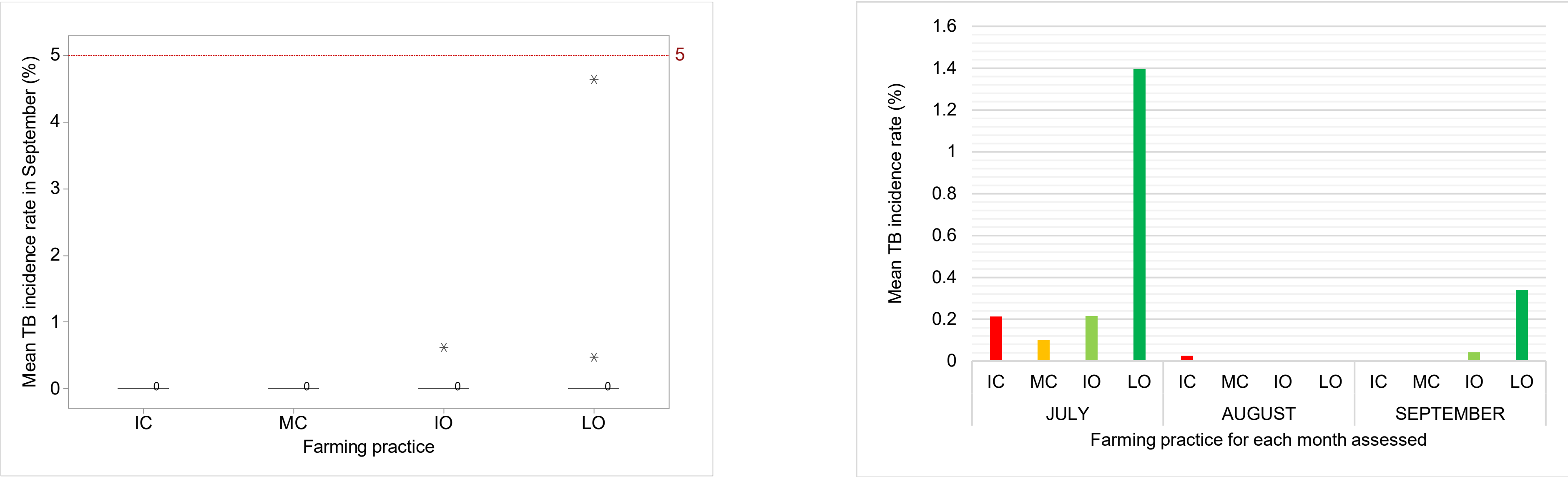


B



C

D

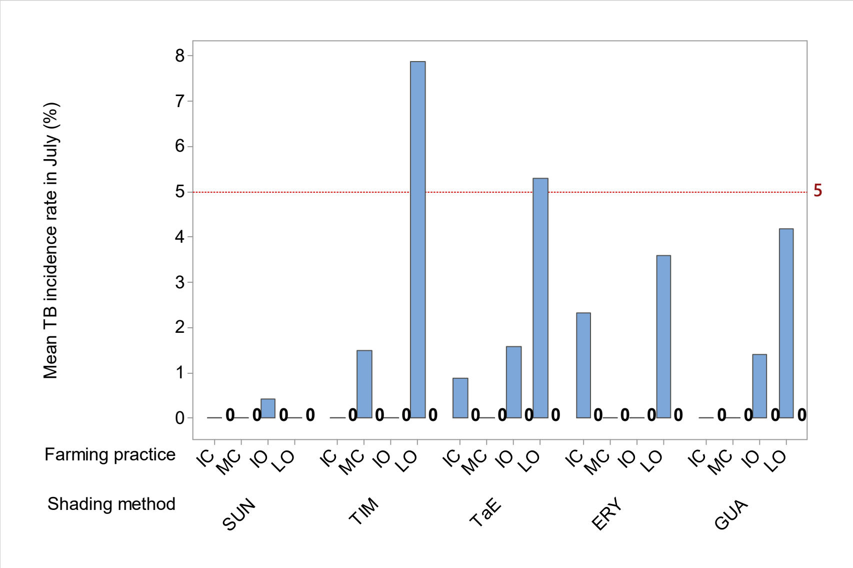


The graphs in Figure 31 show that the mean TB incidence rate did not differ from one assessed AFS to another. The infestation was below the economic threshold for all months assessed and almost nil. However, it is interesting to note that in July and September the LO farming practice showed a striking mean TB incidence rate.

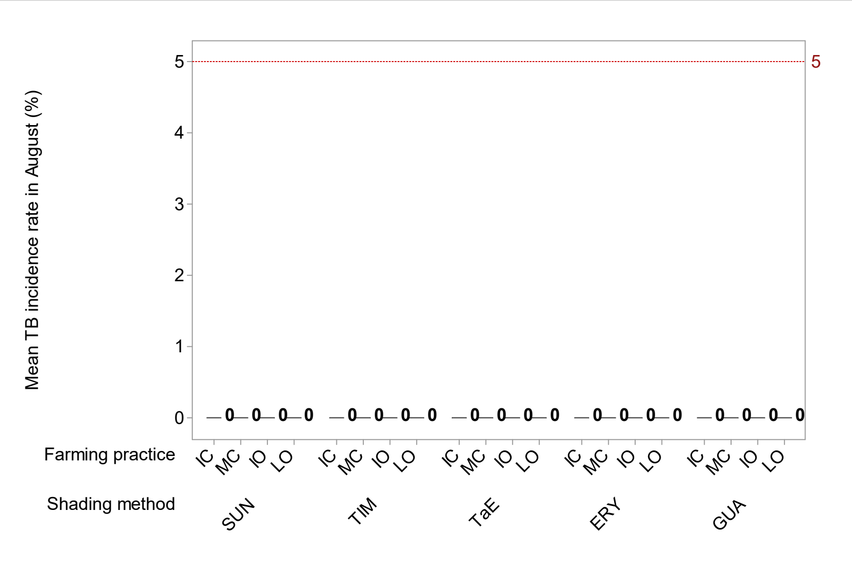
Figure 31. Graphics of the mean *Pellicularia koleroga* incidence rate in relation to agroforestry systems:

A-C: Box and whisker plots of the mean *Pellicularia koleroga* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Pellicularia koleroga* incidence rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 5%.

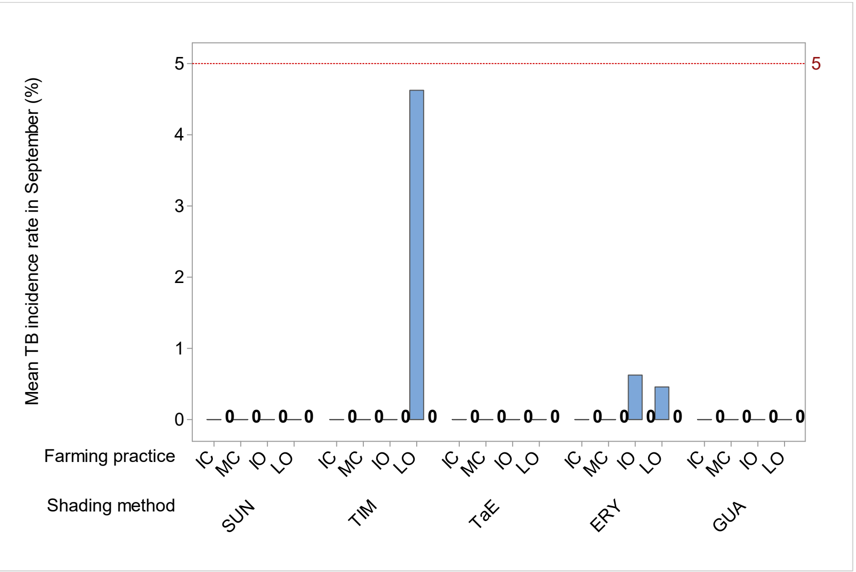
A



B



C



Mean TB incidence rate in September (%)
5
4
3
2
1
0
5
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
Farming practice
IC MC IO LO IC MC IO LO IC MC IO LO IC MC IO LO IC MC IO LO
Shading method
SUN TIM TaE ERY GUA

D

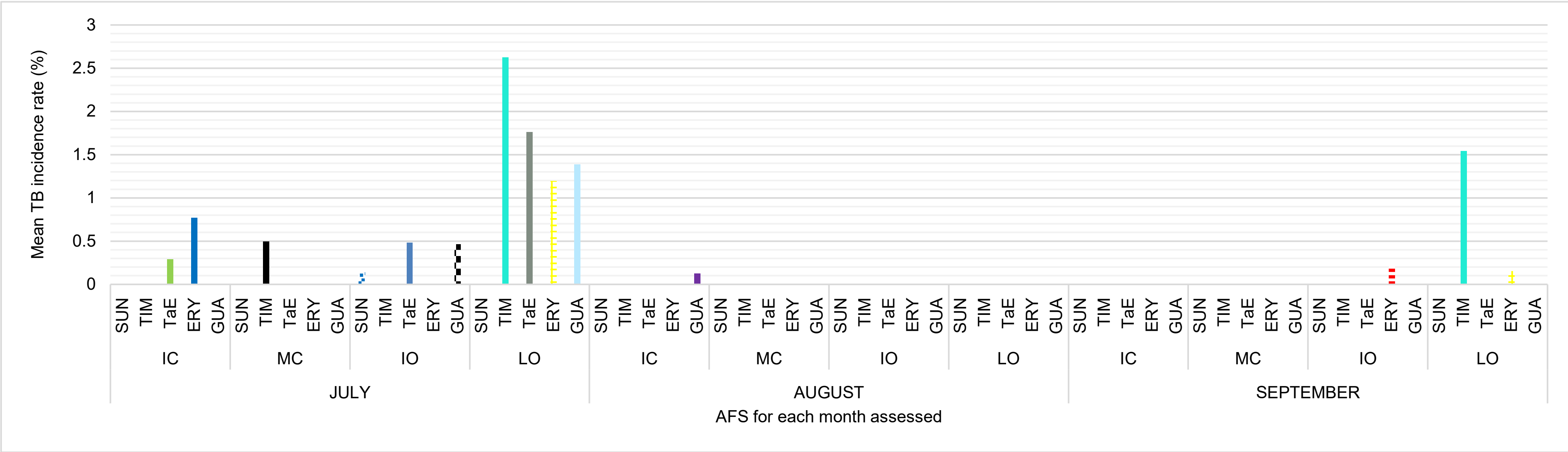


Table 24 shows that neither shading method nor farming practice had a statistically significant impact on the mean TB incidence rate, and there was no interaction between the two. As most of the data amounted to nil, p-value calculation was not possible for August and September.

Table 24: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Pellicularia koleroga* incidence rate (%). P-values below 5% are statistically significant and indicated in bold.

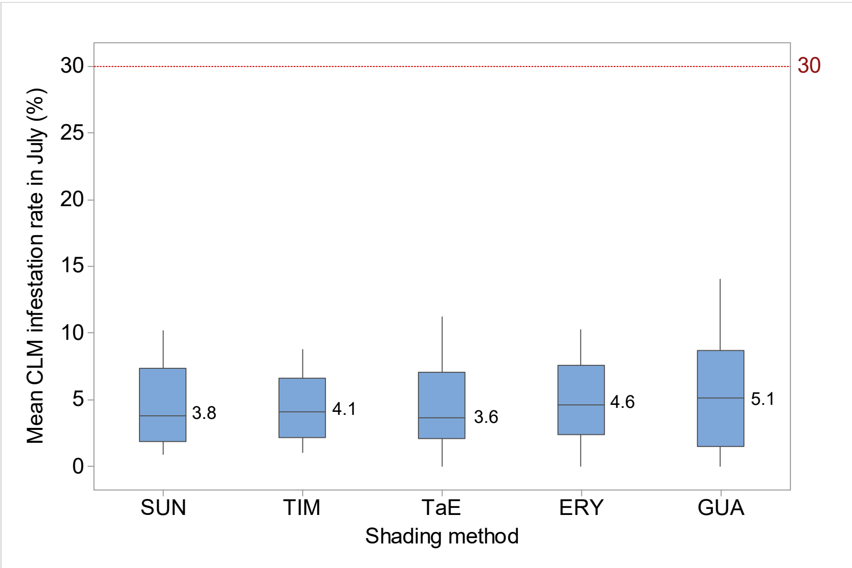
	p-value		
	July	August	September
Shading method	0.787	-	-
Farming practice	0.297	-	-
Shading method*farming practice	0.889	-	-

6.8 *Leucoptera coffeella* infestation

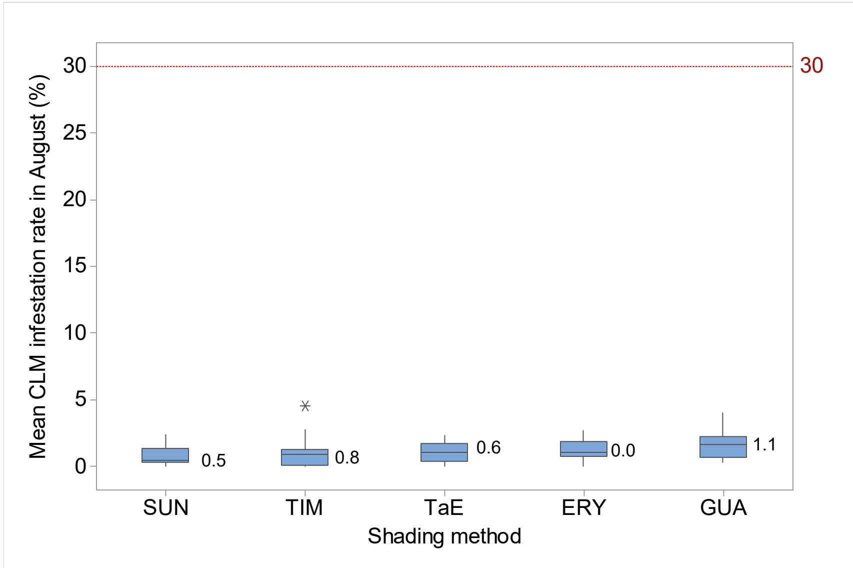
Figure 32 shows that the mean CLM infestation rate did not greatly differ from one shading method to another. The infestation was below the economic threshold for all months assessed. However, the histogram denotes a higher mean CLM infestation rate in July, in comparison with the other months; it also shows that in July and August the GUA shading method had the highest mean CLM infestation rate.

Figure 32. Graphics of the mean *Leucoptera coffeella* infestation rate in relation to the shading method: A-C: Box and whisker plots of the mean *Leucoptera coffeella* infestation rate (%) in relation to the shading method in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Leucoptera coffeella* infestation rate (%) in relation to the shading method in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 30%.

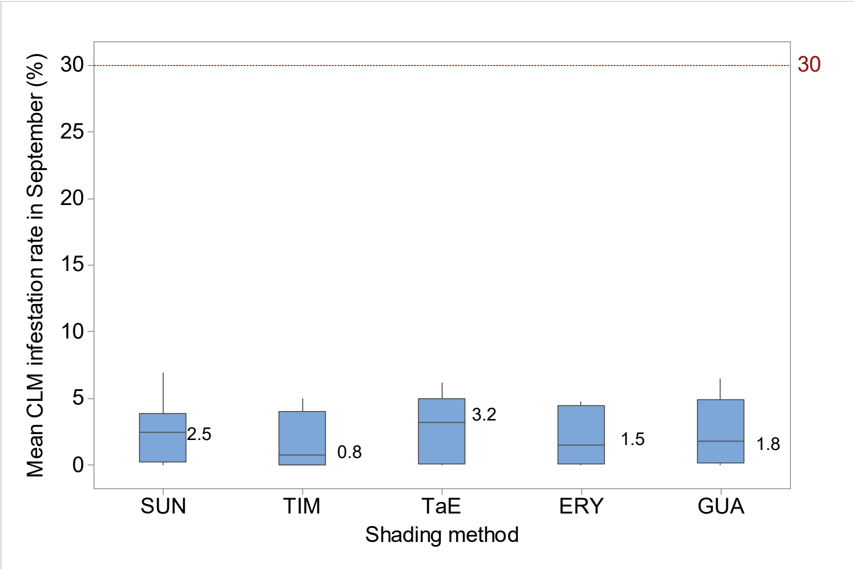
A



B



C



D

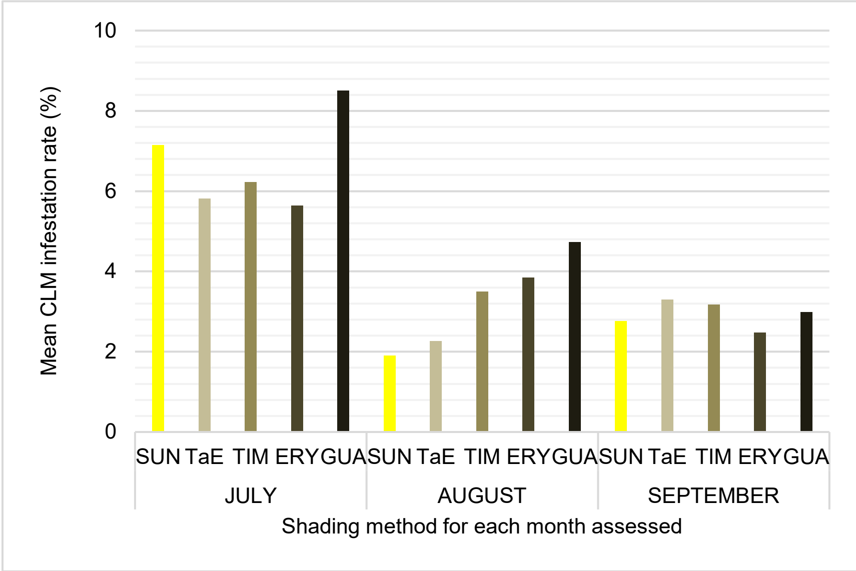
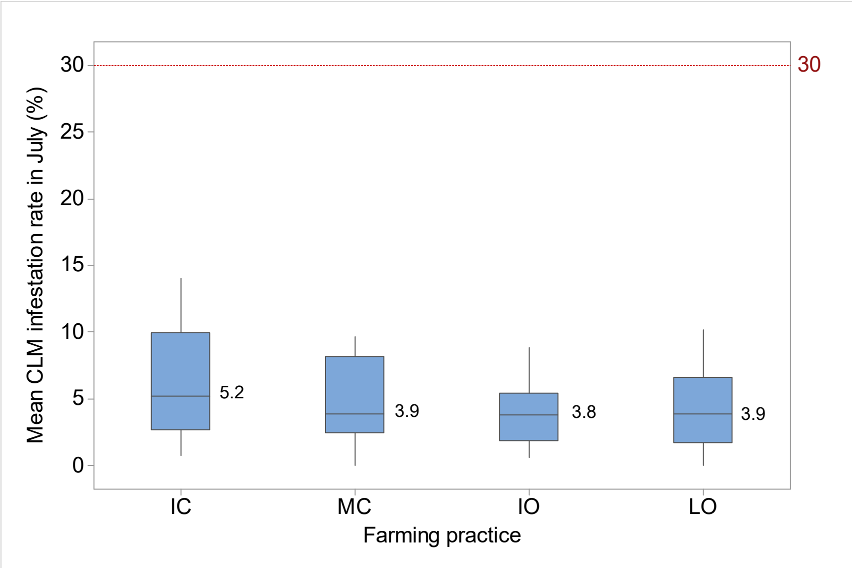


Figure 33 shows that the mean CLM infestation rate does not greatly differ from one farming practice to another. The infestation was below the economic threshold for all months assessed. However, the histogram denotes a higher mean CLM infestation rate in July in comparison with the other months, and shows that in July and August the IC farming practice had the highest mean CLM infestation rate.

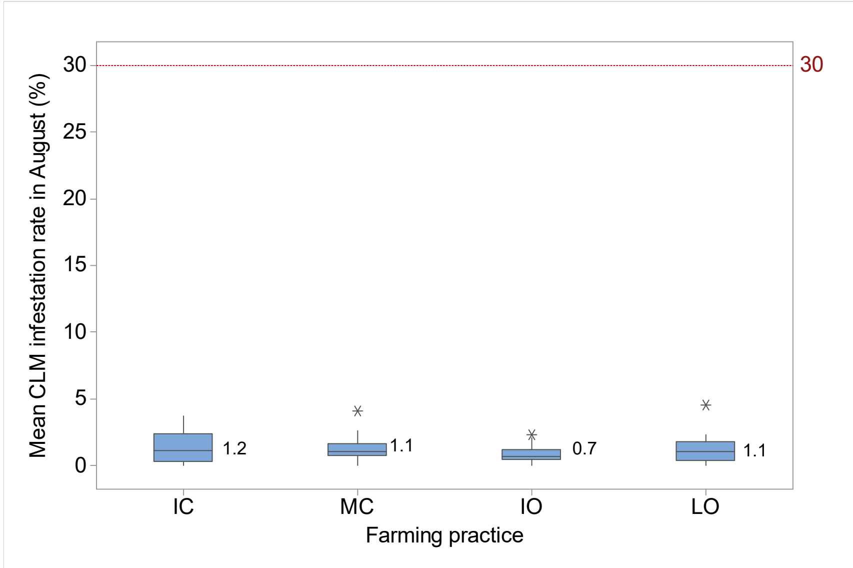
Figure 33. Graphics of the mean *Leucoptera coffeella* infestation rate in relation to the farming practice:

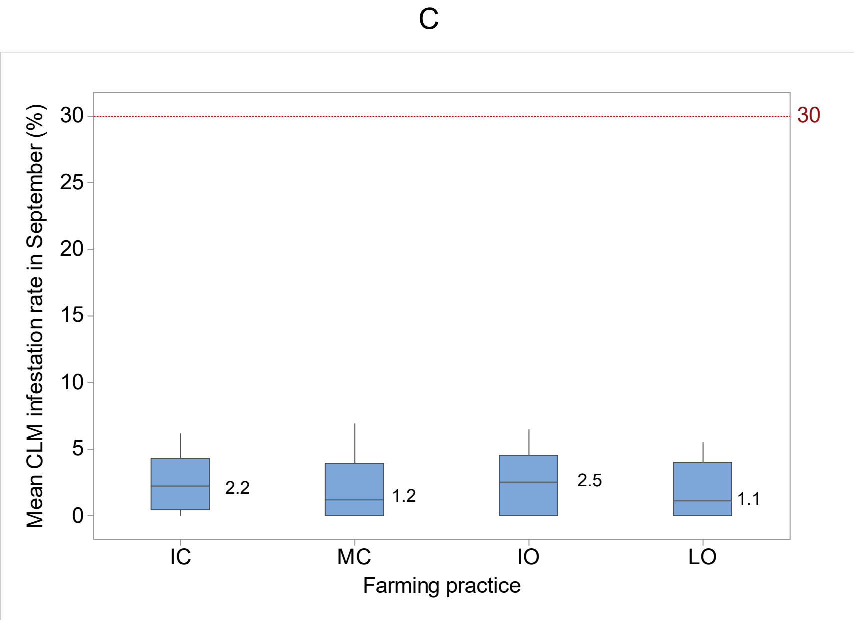
A-C: Box and whisker plots of the mean *Leucoptera coffeella* infestation rate (%) in relation to the farming practice in July, August and September 2018. The numbers near the boxes indicate medians. D: Histogram of the mean *Leucoptera coffeella* infestation rate (%) in relation to the farming practice in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 30%.

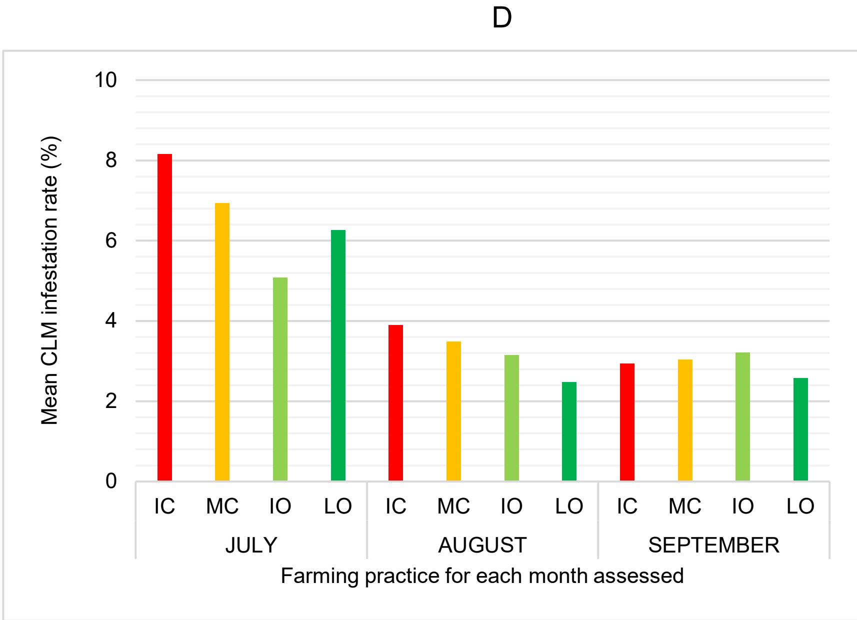
A



B



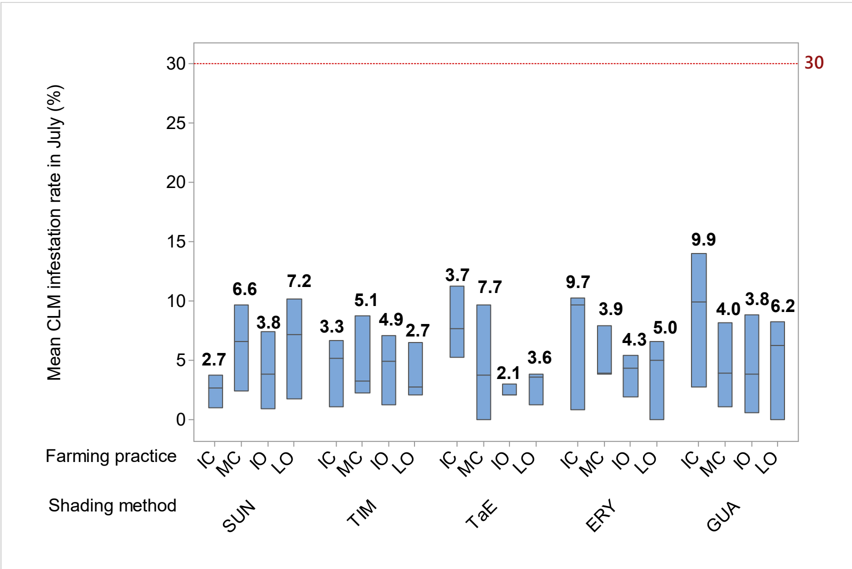




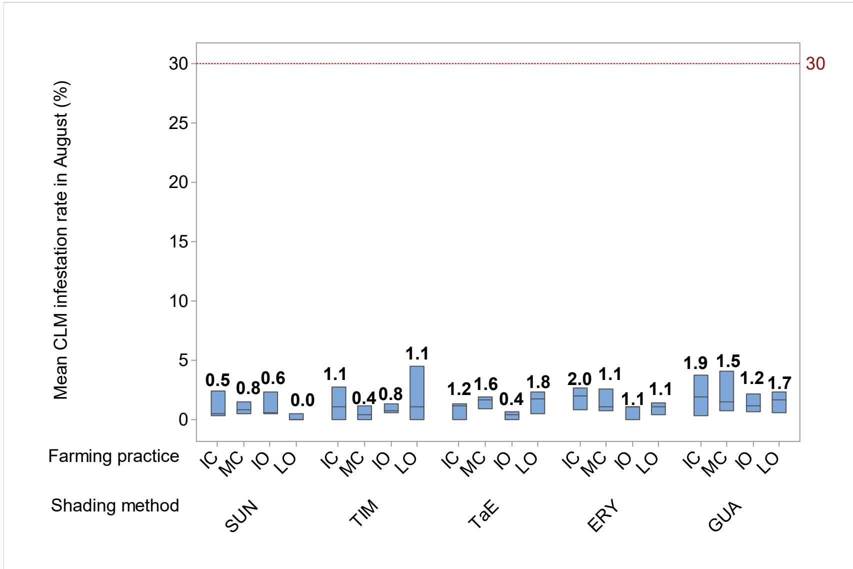
In Figure 34, the graphs show that with respect to CLM infestation the worst AFS were as follows for July, August and September: GUA-IC with a median 9.9%, ERY-IC with a median 2% and GUA-IC with a median 5.3%. The best AFS for the same month were: TaE-IO with a median of 2.1%, SUN-LO with a median 0% and TIM-IC with a median 0.3%. The histogram seems to show that for each month the mean CLM infestation rate increased with the shade quantity. Generally, the mean CLM incidence rate was higher for the ERY and/or GUA shading methods, except for the month of September.

Figure 34. Graphics of the mean *Leucoptera coffeella* infestation rate in relation to agroforestry systems: A-C: Box and whisker plots of the mean *Leucoptera coffeella* infestation rate (%) in relation to agroforestry systems in July, August and September 2018. The numbers above the boxes indicate medians. D: Histogram of the mean *Leucoptera coffeella* infestation rate (%) in relation to agroforestry systems in July, August and September 2018. In all graphs, the red reference line indicates the economic threshold, which is 30%.

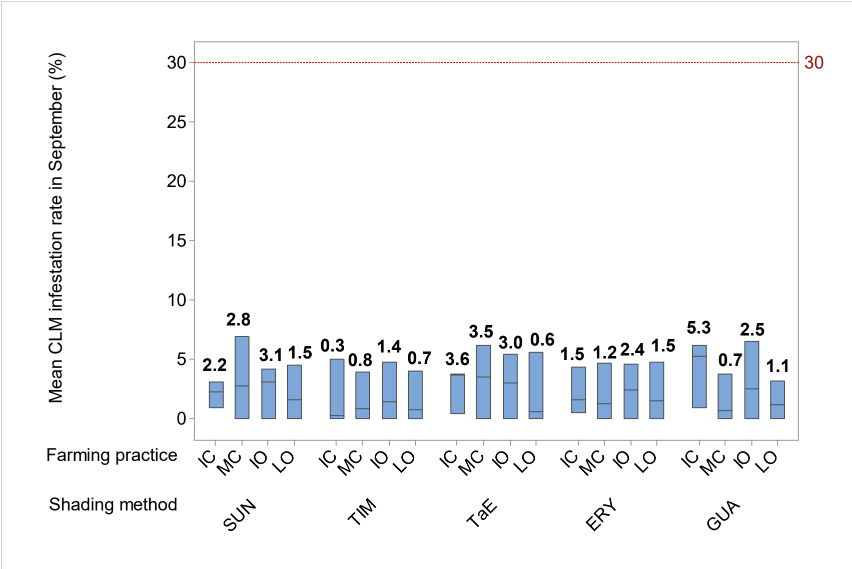
A



B



C


Mean CLM infestation rate in September (%)
30
25
20
15
10
5
0
30
2.2 2.8 3.1 1.5
0.3 0.8 1.4 0.7
3.6 3.5 3.0 0.6
1.5 1.2 2.4 1.5
5.3 0.7 2.5 1.1
Farming practice
IC MC IO LO IC MC IO LO IC MC IO LO IC MC IO LO IC MC IO LO
Shading method
SUN TIM TaE ERY GUA

D

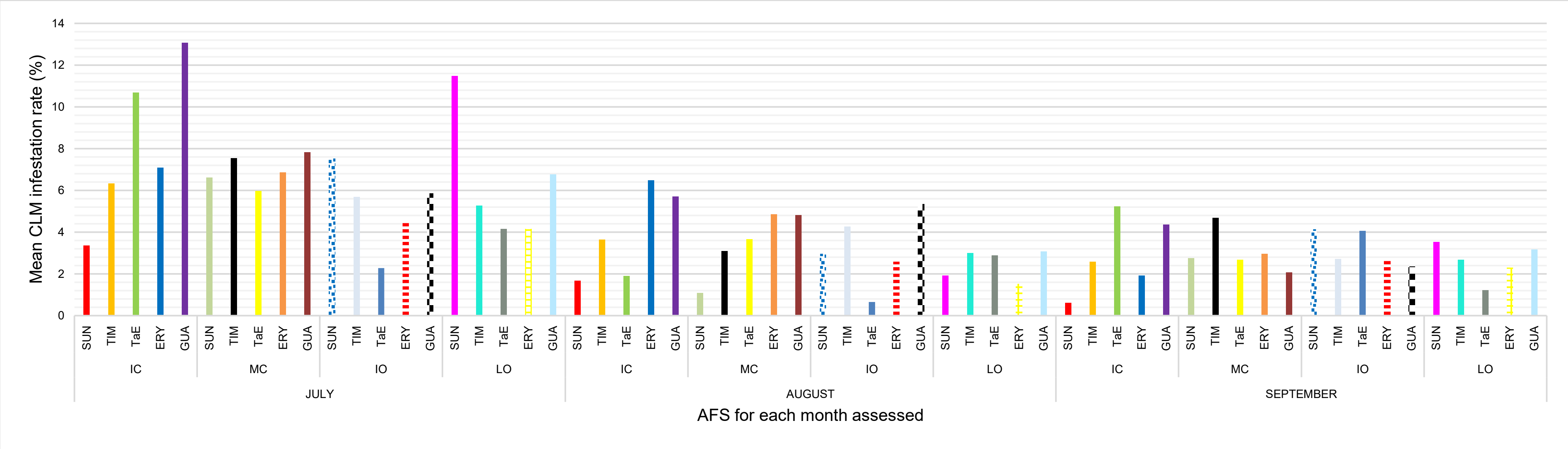


Table 25 shows that neither shading method nor farming practice had a statistically significant impact on the mean CLM infestation rate, and further, there was no interaction between shading method and farming practice.

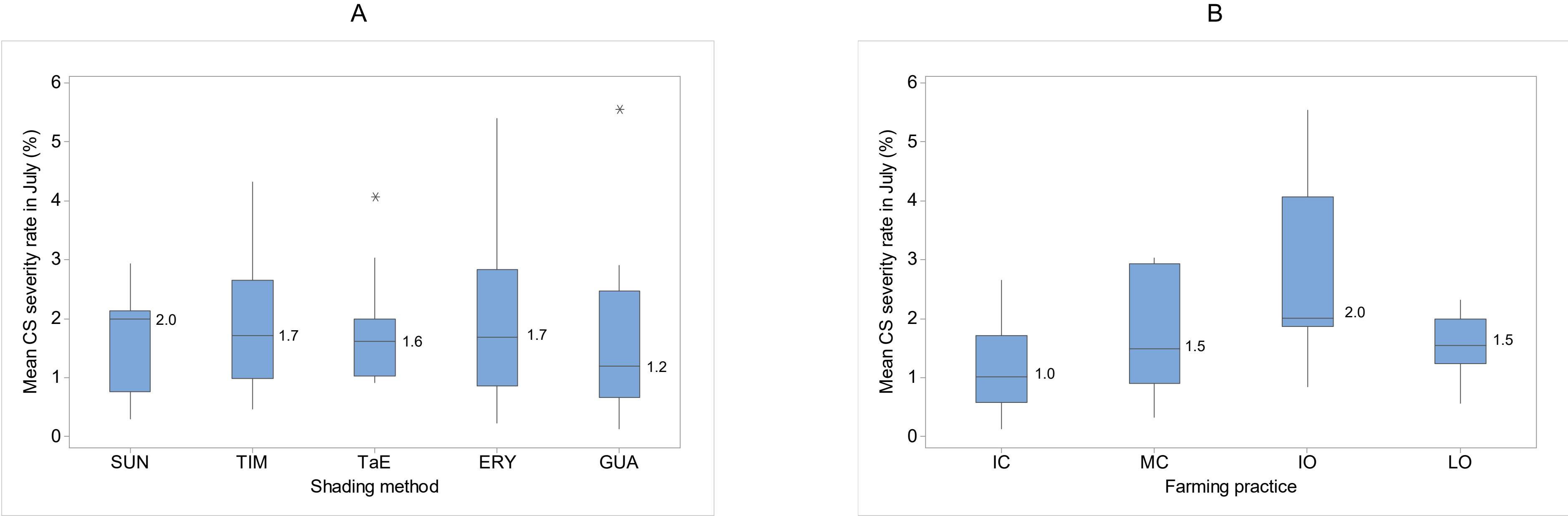
Table 25: Monthly p-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Leucoptera coffeella* infestation rate (%). P-values below 5% are statistically significant and indicated in bold.

	p-value		
	July	August	September
Shading method	0.878	0.503	0.660
Farming practice	0.703	0.549	0.700
Shading method*farming practice	0.259	0.295	0.272

6.9 *Colletotrichum spp*. severity

The box and whisker plots of Figure 35 show that in July the mean CS severity rate was at its lowest with the GUA shading method (median 1.2%) and at its highest with the IO farming practice (median 2%). According to the bottom graph and also in July, the mean CS severity rate was at its lowest with a GUA-IO AFS (mean 0.6%) and at its highest with an ERY-IO AFS (mean 4.1%).

Figure 35. Box and whisker plots of the mean *Colletotrichum spp.* severity rate in July (%) in relation to the shading method (A), the farming practice (B) and agroforestry systems (C). The numbers near or above the boxes indicate medians.



C

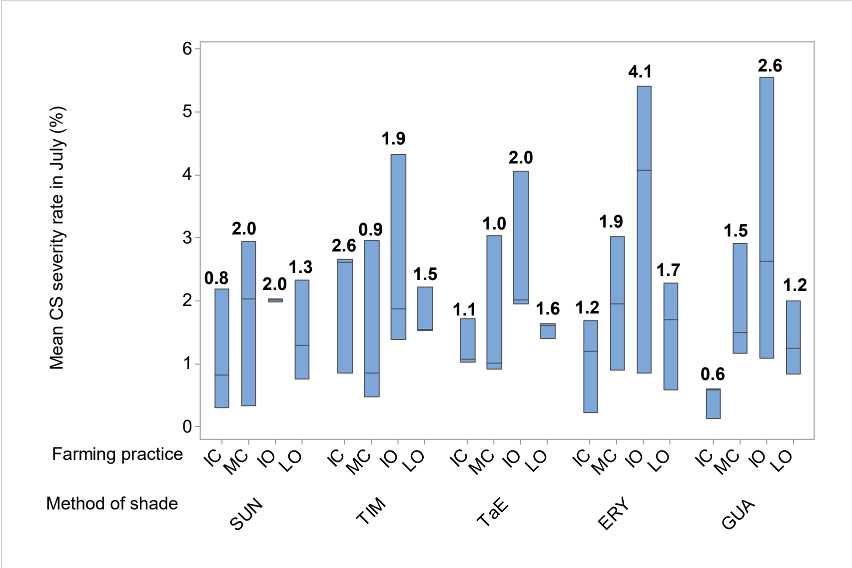


Table 26 shows that the farming practice significantly impacted the mean CS severity rate in July (p-value= 0.3%).

Table 26: P-values obtained for the shading method, farming practice and interaction between the two in relation to the mean *Colletotrichum spp.* severity rate (%) in July. P-values below 5% are statistically significant and indicated in bold.

	p-value
	July
Shading method	0.893
Farming practice	**0.003**
Shading method*farming practice	0.925

According to July's measurements shown in Table 27, experimental units applying an IO farming practice had a mean CS severity rate statistically and significantly between 0.5%-3% higher than those applying an IC farming practice, in addition to a mean CS severity rate statistically and significantly between 0.1%-2% higher than those applying an LO farming practice.

Table 27: Results of Tukey's tests for multiple comparison intervals of the farming practices in July in relation to the mean *Colletotrichum spp.* severity rate (%). P-values below 5% are statistically significant and indicated in bold.

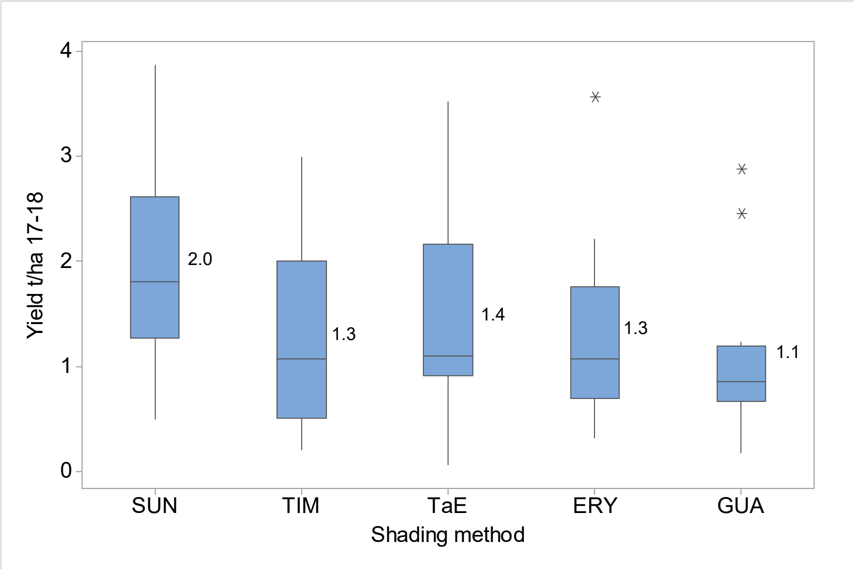
July		
Farming practice		
Difference between mean rates	*95% confidence intervals (mean CS severity rate difference in %)*	*Adjusted p-value*
IC-MC	(-1.656; 0.545)	0.533
IC-IO	(-2.670; -0.47)	**0.003**
IC-LO	(-1.45; 0.75)	0.828
MC-IO	(-2.115; 0.086)	0.08
MC-LO	(-0.895; 1.306)	0.958
IO-LO	(0.12; 2.321)	**0.025**

6.10 Yield in 2017-2018

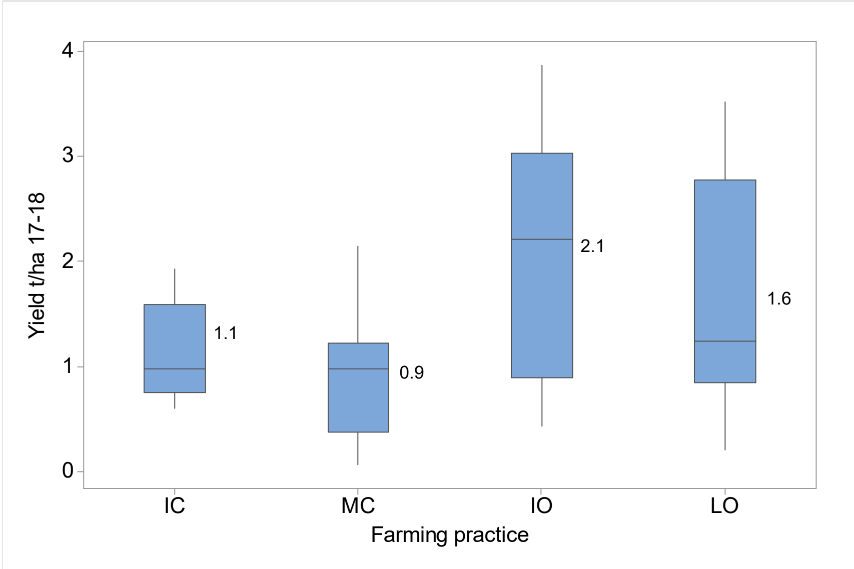
The yield figures come from the EECA staff and allow for a more accurate hypothesis to be proposed concerning the impact of shading methods and farming practices on Robusta coffee PDD. The yield sums up the weight of all the ripe cherries harvested in one experimental unit. According to Figure 36, the mean yield during production year 2017-2018 appears to be higher with IO (mean 2.1 t/ha) and LO (mean 1.6 t/ha) farming practices, in comparison with IC (mean 1.1 t/ha) and MC (mean 0.9 t/ha) farming practices. As to the shading method, results indicate that the SUN shading method had the highest mean yield (mean 2 t/ha). The other shading methods present yields between 30% to 45% smaller than the SUN one. The comparison of AFS yields shows that the 4 highest mean yields were obtained with the following AFS: SUN-IO (mean 3.1 t/ha), TaE-IO (mean 2.1 t/ha), TaE-LO (mean 1.9 t/ha) and ERY-LO (mean 1.9 t/ha). The 5 lowest mean yields were obtained with the following AFS: GUA-MC (mean 0.7 t/ha), GUA-IC (mean 0.8 t/ha), ERY-IC (mean 0.8 t/ha), TaE-MC (mean 0.8 t/ha) and TIM-MC (mean 0.8 t/ha).

Figure 36. Box and whisker plots of the 2017-2018 mean yield (t/ha) in relation to the shading method (A), the farming practice (B) and AFS (C). The numbers near or above the boxes indicate means.

A



B



C

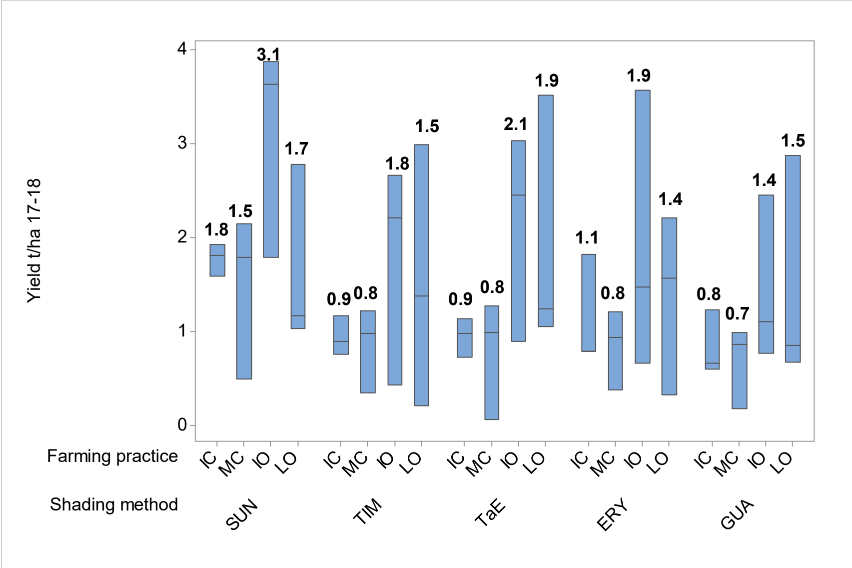


Table 28 shows that the shading method significantly impacted the mean yield during production year 2017-2018 (p-value= < 0.1%).

Table 28: P-values obtained for the shading method, farming practice and interaction between the two in relation to the mean yield during production year 2017-2018 (t/ha). P-values below 5% are statistically significant and indicated in bold.

	p-value
	2017-2018
Shading method	**< 0.001**
Farming practice	0.337
Shading method*farming practice	0.221

According to the results shown in Table 29, in production year 2017-2018 the experimental units applying the SUN shading method had a mean yield between 0.03-1.2 t/ha, statistically and significantly higher than those applying the TIM shading method, 0.1-1.02 t/ha higher than those applying the TaE shading method, 0.23-1.15 t/ha higher than those applying the ERY shading method and 0.44-1.36 t/ha higher than the GUA shading method.

Table 29: Results of Tukey's tests for multiple comparison intervals of the shading methods during production year 2017-2018 in relation to the mean yield (t/ha). P-values below 5% are statistically significant and indicated in bold.

2017-2018		
Shading method		
Difference between mean rates	*95% confidence intervals (mean yield difference in t/ha)*	*Adjusted p-value*
SUN-TIM	(0.027; 1.195)	**0.001**
SUN-TaE	(0.091; 1.017)	**0.013**
SUN-ERY	(0.228; 1.154)	**0.001**
SUN-GUA	(0.435; 1.361)	**< 0.001**
TIM-TaE	(-0.642; 0.284)	0.796
TIM-ERY	(-0.505; 0.421)	0.999
TIM-GUA	(-0.298; 0.628)	0.839
TaE-ERY	(-0.326; 0.6)	0.910
TaE-GUA	(-0.119; 0.807)	0.225
ERY-GUA	(-0.256; 0.670)	0.698

6.11 Shade percentages

The results in Figure 37 show that the highest shade percentage was obtained with the ERY shading method, with a mean shade quantity of 29.5%. It can also be seen that combining ES and MB trees resulted in the lowest mean shade quantity with 9.2%, excluding the SUN shading method. It is interesting to point out that there was no striking difference between the GUA and ERY shading methods with respect to the mean shade quantity. According to the bottom graph, the comparison of treatments combining the period of the day and shading method shows that the 2 highest mean shade quantities were obtained with the following treatments: ERY 0900-1030 with a median 36.8% and GUA 1400-1530 with a median 31%.

Figure 37. Box and whisker plots of the 2018 mean shade quantity (%) in relation to the shading method (A), and the shading method combined with the period of the day (B). The numbers in bold near or above the boxes indicate medians and those not in bold are means.

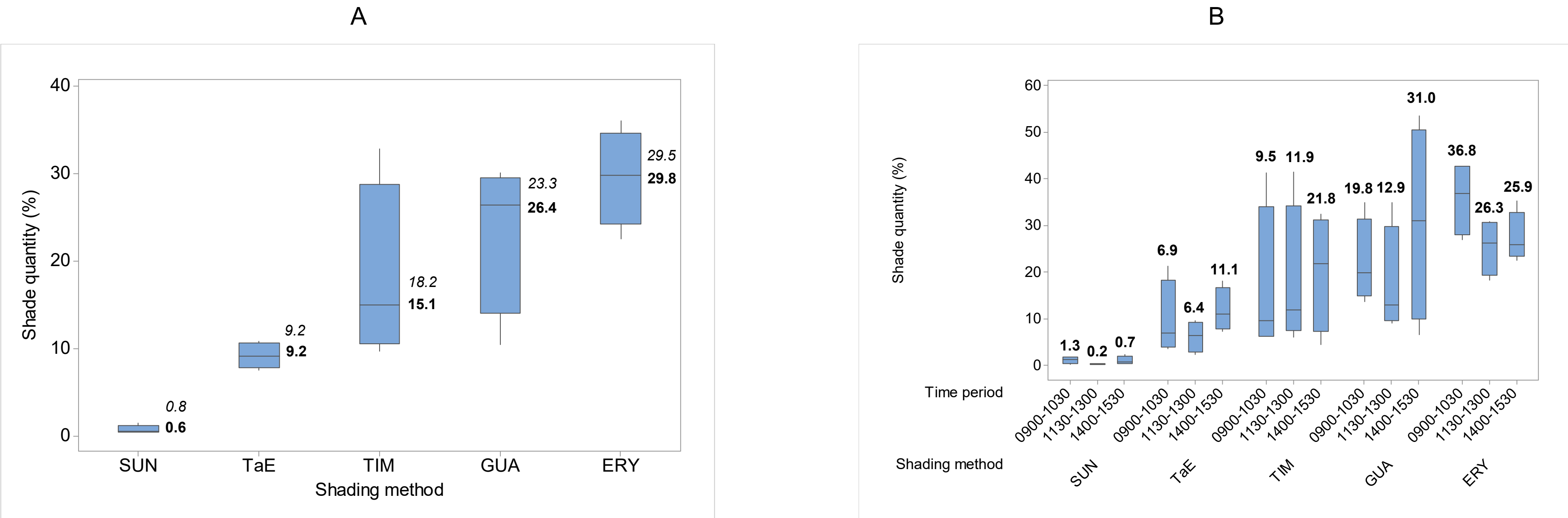


Table 30 shows that the shading method significantly impacted the mean shade quantity in 2018 (p-value= < 0.1%).

Table 30: P-values obtained in 2018 for the shading method, the period of the day and interaction between the two in relation to the mean shade quantity (%). P-values below 5% are statistically significant and indicated in bold.

	p-value
	July-September 2018
Shading method	**< 0.001**
Time period (period of the day)	0.6
Shading method*time period	0.554

According to the results shown in Table 31, the experimental units applying the SUN shading method had a mean shade quantity rate statistically and significantly between 10 and 50 times lower than those applying the TIM shading method, 5 and 33 times lower than those applying the TaE shading method, 17 and 111 times lower than those applying the ERY shading method, 13 and 100 times lower than those applying the GUA shading method. Further, the experimental units applying the TaE shading method had a mean shade quantity rate statistically and significantly between 1.3 and 8.3 times lower than those applying the ERY shading method.

Table 31: Results of Tukey's tests for multiple comparison intervals of shading methods in 2018 in relation to the mean shade quantity (%). P-values below 5% are statistically significant and indicated in bold.

July-September 2018		
Shading method		
Difference between mean rates	*95% confidence intervals (mean shade quantity in % with the log transformation)*	*Adjusted p-value*
SUN-TIM	(-1.778; -0.981)	**< 0.001**

SUN-TaE	(-1.524; -0.727)	**< 0.001**
SUN-ERY	(-2.029; -1.232)	**< 0.001**
SUN-GUA	(-1.9; -1.103)	**< 0.001**
TIM-TaE	(-0.145; 0.652)	0.329
TIM-ERY	(-0.65; 0.147)	0.335
TIM-GUA	(-0.521; 0.276)	0.874
TaE-ERY	(-0.904; -0.107)	**0.01**
TaE-GUA	(-0.774; 0.023)	0.069
ERY-GUA	(-0.269; 0.528)	0.85

6.12 Pictures of diseases

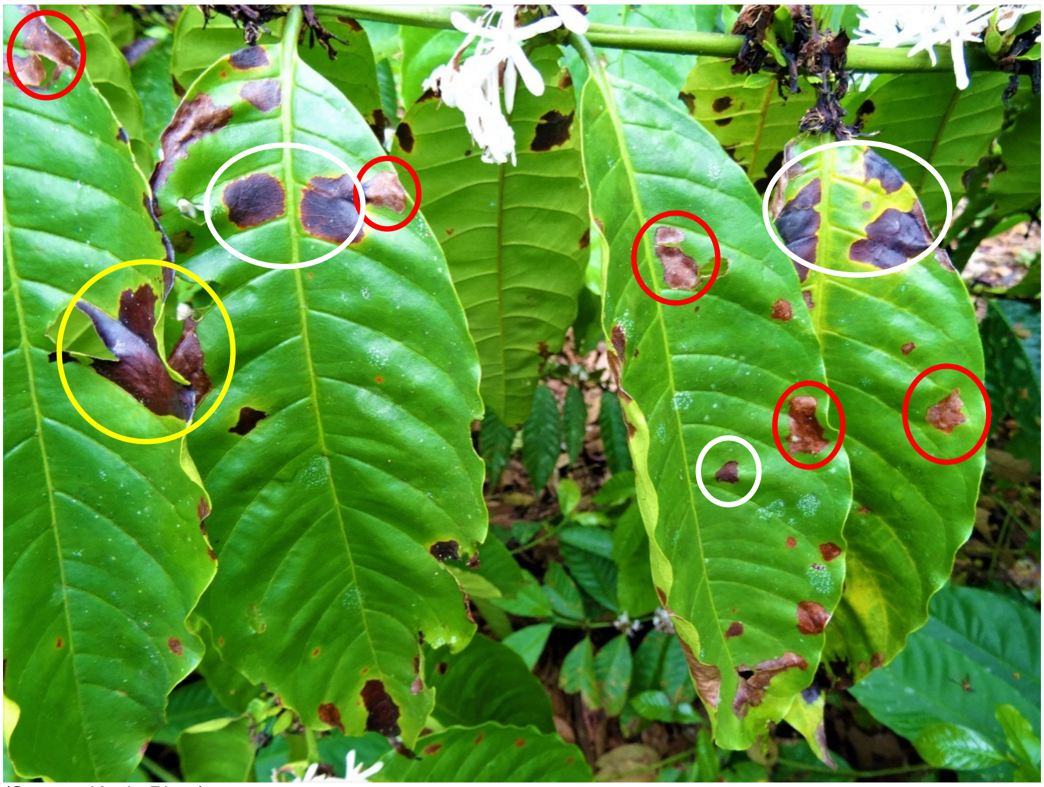
Erreur ! Source du renvoi introuvable. shows that both PS and CS fungi have similar foliar symptoms that are able to amalgamate.

Picture 16. Robusta coffee leaf infected by *Colletotrichum spp*. (red circles) and *Phoma spp*. (white circles), from evaluated field

(Source: Kevin Piato)

Erreur ! Source du renvoi introuvable. shows that CS, PS and CLM symptoms may occur simultaneously on the same leaf.

Picture 17. Robusta coffee leaves infected by *Colletotrichum spp*. (white circles), *Phoma spp*. (yellow circles) and infested by *Leucoptera coffeella* (red circles)



(Source: Kevin Piato)

6.13 Pictures of shade trees

Erreur ! Source du renvoi introuvable. shows that the MB tree provided little shading because of its low height.

Picture 18. Shade provided by a *Myroxylon balsamum* tree, from surveyed field

(Source: Kevin Piato)

Erreur ! Source du renvoi introuvable. shows that banana plants were higher than MB trees.

Picture 19. Experimental unit with *Myroxylon balsamum* trees and banana plants, from surveyed field

(Source: Kevin Piato)

Erreur ! Source du renvoi introuvable. shows that IE trees were higher than banana plants.

Picture 20. *Inga edulis* trees with *Musa spp*. trees below them, from surveyed field

(Source: Kevin Piato)

Erreur ! Source du renvoi introuvable. shows that the total green cover of ES trees was not uniform.

Picture 21. *Erythrina spp*. trees in the same experimental unit, from surveyed field. Above: less developed trees, bottom: well developed trees

(Source: Kevin Piato)

Erreur ! Source du renvoi introuvable. shows that the canopies of MB, IE and ES

Picture 22. Canopies of *Myroxylon balsamum* tree (upper), *Inga edulis* (middle) and *Erythrina spp*. (bottom), from surveyed field

(Source: Kevin Piato)

trees have different shapes.

7. Discussion

7.1 *Xylosandrus morigerus* infestation

As observed in the present trial, BTB represents a serious threat to Robusta coffee plantations. It is reported that BTB or *Xylosandrus spp*. preferably attacks weak coffee plants lacking fertilisation, since a good level of plant fertilisation reduces the development of ambrosia fungus, which is associated with BTB feeding (Greco and Wright, 2015; Jaramillo et al., 2015). The fact that conventional farming practices showed a higher BTB infestation than groups practicing organic farming may be explained by a difference in fertilisation between these two farming practices. Indeed, chemical fertilisers were applied on 17th May 2018 in IC and MC experimental units and the same day, the soil received a 12.35 mm rainfall. This important rainfall added to others on 20th May (53 mm) and 25th May (87.5 mm) may give evidence of important NO_3^- leaching losses, reinforced by the fact that the N quantity applied was mainly in NO_3^- form. It is well established that organic cropping systems reduce N leaching losses and N mineralisation, increase the soil content in N and organic matter, in addition to enhancing enzymatic and microbial activity in the soil (Poudel et al., 2002; Chang et al., 2007; Sauvadet et al., 2019). This could mean that fertilisation in the IC and MC experimental units may have been inefficient, resulting in the coffee plants being exposed to insufficient nutrients. The consequence of nutrient limitations on BTB infestation may have been enhanced by the use of herbicides in the IC and MC experimental units, which may in turn have reduced the population of biological agents controlling BTB, especially BB and ants of the *Crematogaster*, *Leptothorax*, *Pheidole*, *Pseudomyrmex* and *Solenopsis* genus (Jaramillo et al., 2015). What is more, the use of paraquat and Goal Tender in experimental units with conventional farming practices markedly reduced the aboveground weed biomass, when compared to the experimental units applying organic farming practices, as can be seen in Table 13. Consequently, in experimental units applying organic farming there may have been fewer N leaching losses and therefore a higher N soil content than in those applying conventional farming (Poudel et al., 2002). It is very likely that coffee plants under conventional farming practices are affected by nutrient limitations which better attract BTB. The same nutrient limitations may also explain why the yields observed in the present study were more plentiful in organic farming practices than in conventional ones (Figure 36); it could also be that the greater BTB infestation observed in conventional farming plots contributed to notably reducing their yield. According to a Colombian study, the major part of coffee plant weeds are BTB host plants, especially *Verbena littoralis* which can be found in Ecuatorian Robusta coffee plantations (Benavides, 1961); it may then be possible that removing all weed increases BTB infestation on coffee plants, since BTB infestation is no longer diluted among several plant species.

The results also point out that shade reduces the BTB infestation level, the GUA shading method significantly so. The effectivess of shade as reducing BCTB infestation has also been demonstrated by Bukomeko's study (Bukomeko et al., 2017). The same tendencies appeared with the ERY and TaE shading methods, but not significantly, ERY experimental units presenting less BTB infestation than those with TaE shade. The GUA shading method presented one of the highest mean shade percentages, suggesting that a great shade quantity is necessary to impact BTB infestation. As shown in Figure 36, the plots applying the SUN shading method yielded more than those applying the TIM, TaE, ERY and GUA shading methods, a fact also shown by Campanha et al. (2004). Since phenolic compounds, important antimicrobial barriers for plants, have shown more presence in leaves and fruit of shaded coffee plants, than in those under full sun (Salgado et al., 2008; Somporn et al., 2012), coffee plants in full sun are more prone to disease and pest (Carvalho et al., 2001). This fact could explain why a higher BTB infestation rate was observed in the SUN shading method, as compared to the GUA shading method. It has been demonstrated that the presence of shelter trees in a coffee plantation allow N leaching losses to decrease (Babbar and Zak, 1995; Tully et al., 2012). It could thus be that the IE shelter tree helps to reduce N leaching losses, in comparison with the SUN experimental units. Reducing N leaching losses results in a higher soil content of N and better avaibility thereof for the Robusta coffee plants, making it less attractive for BTB.

The ERY shading method, which presents a rate of shade quantity very similar to the GUA shading method, did not impact BTB infestation, possibly meaning that not only does the amount of shade impact BTB infestation, but also the type of shelter tree used. For instance, it has been pointed out that shelter trees which exude copious sap such as *Ficus natalensis* are associated with a reduced BCTB infestation, the sap being a repellent (Bukomeko et al., 2017). However, in the case of the present study, it could be that the IE tree had an adverse effect: indeed, it has been seen in Colombia that IE is a host for BTB (Benavides, 1961). It is therefore likely that IE trees attract BTB, consequently reducing its impact on Robusta coffee plants. Further research is needed to firmly corroborate this hypothesis. It could also be that the difference observed between the GUA and SUN shading methods, with respect to BTB infestation, and not observed with the ERY shading method, is due to the leaf polyphenols level. It has been demonstrated that ES leaves contain fewer polyphenols than IE leaves, and therefore decompose faster than IE leaves (Palm and Sanchez, 1990). It has also been demonstrated that the presence of ES makes for better crop yields than IE (Salazar et al., 1993). So the different leaf contents would not explain why BTB infestation is reduced in the presence of IE trees but not ES when compared to Robusta coffee plants in full sun, since the latter are better fertilised with ES trees and BTB prefers plants where nutrients are lacking. This observation could point out the attractive role of IE trees. It is clear that other factors may explain the fact that the GUA shading method provides better protection against BTB than the SUN one, especially when the microclimate change induced by the trees favours BB presence, BB prefering a highly humid environment (Staver et al., 2001). And as mentioned above, BB could be a biological control agent of BTB.

7.2 *Hypothenemus hampei* infestation – *Beauveria bassiana* presence

In September, the CBB infestation rate in IC plots was between 2%-12%, significantly higher than in IO and LO plots. It also is interesting to point out that the BB presence rate in IC plots was between 3%-17%, significantly higher than in IO plots and between 2% and 16% higher than in LO plots, meaning that there could be a positive correlation between the CBB infestation rate and the BB presence rate. That is the correlation highlighted in **Erreur ! Source du renvoi introuvable.**, and it is statistically significant with a p-value < 0.001. BB presence could be higher, since there is more CBB to attack. However, it does not necessarily mean that there is more BB in the field. Indeed, BB presence was determined according to the berries attacked by borers and therefore, it is possible that there was more BB in the soil of IO or LO plots, but as there were less borer attacked berries in those plots, there were also fewer borer attacked berries infected by BB, as **Erreur ! Source du renvoi introuvable.** points out. Similar results indicate the same positive correlation between BB presence and CBB infestation in a Mexican experiment (Rosa et al., 2000). Another explanation supporting this correlation is that the rain splash dispersal is more pronounced in conventional plots, since there is little crop residue on the ground and no weed cover, two factors which can reduce dispersal of BB fungus spores by rain splash (Yang, 1992; Bruck and Lewis, 2002).

Figure 38. Correlation between the mean *Beauveria bassiana* presence rate in September and the mean *Hypothenemus hampei* infestation rate in September. The regression line is figured in red.

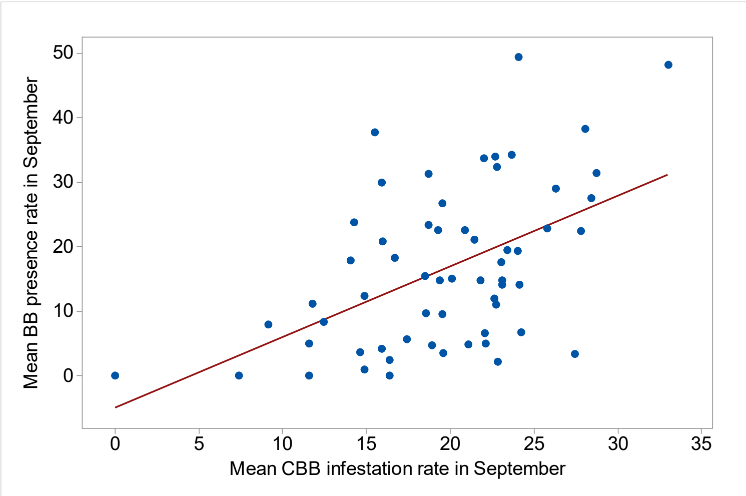
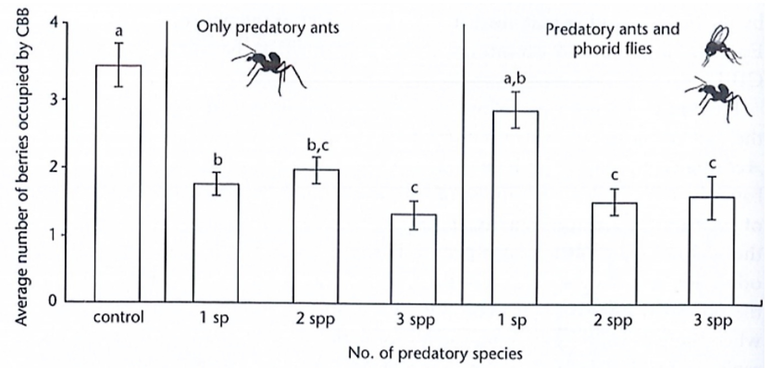


Figure 36 shows that organic Robusta coffee plots yielded more than conventional coffee plots. In general, with a higher yield, a higher CBB infestation rate could be expected because the ripe berries emit volatile compounds which can attract adult female CBB (Gutiérrez and Ondarza, 1996; Ortiz et al., 2004; Mendesil et al., 2009), in addition to more ripe or dead berries potentially dropping to the ground and aggravating the CBB infestation factor, as CBB reproduction continues inside the grounded berries (Damon, 2000). However, in the case of the present study, more CBB infestation was found in IC plots, implying that the yield could not explain the difference in CBB infestation between organic and conventional plots. To our way of thinking, it is more likely that the weeds removed in IC plots, had negative effects on CBB. It has been shown that several plants can repel CBB, such as the *Lantana camara*, which is commonly found as a weed in coffee fields (Castro et al., 2017), making it likely that repellent or attractive weeds present in IO and LO plots would explain why there is less CBB infestation there. Pohlan et al. (2008) have even proved that a cover crop helps reduce CBB populations, since it offers habitats for their natural enemies.

There is another explanation for the results at hand, whereby totally removing weeds reduces ant populations, and it is proved that decreased ant populations result in increased CBB (Philpott and Armbrecht, 2006). It has equally been proved that more than 7 ant genera, among other natural enemies, can prey on infested berries and reduce CBB infestation by up to 27% (Bustillo et al., 2002; Armbrecht and Gallego, 2007; Morris et al., 2017). It is therefore important to keep complex vegetation within the agroecosystem that will provide habitats for several ant genera. For instance, the CBB predator *Pheidole synanthropica* nests on the ground, whereas the CBB predator *Azteca* needs trees to nest and forage. **Erreur ! Source du renvoi introuvable.** shows that the preservation of several ant species within the field provides better CBB control (Perfecto and Vandermeer, 2015). In IO and LO plots more ant species are present, resulting in better CBB control.

Figure 39. Diversity of predatory ant species has an impact on average number of berries occupied by *Hypothenemus hampei*

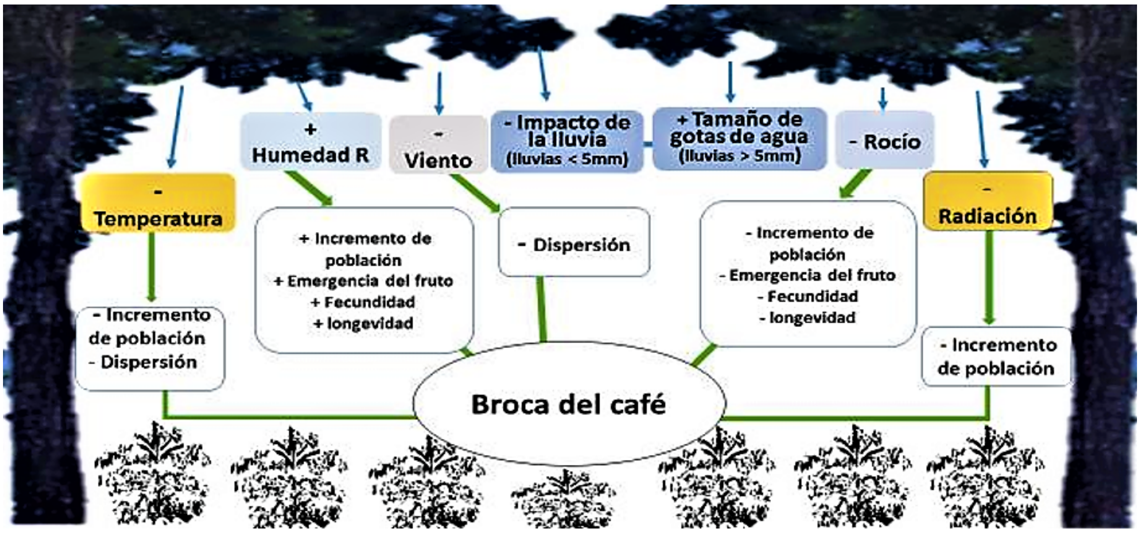


(Source: Perfecto and Vandermeer, 2015)

Although it is not statistically significant, Figure 17 seems to indicate that the BB presence rate tends to increase with the amount of shade. The SUN shading method

presents the lowest rates of BB presence. The fact that shelter trees enhance the living conditions of BB by buffering and lowering temperature and keeping moisture in the agroecosystem, could explain this. It has been reported that a shaded and UVB-protected environment can enhance BB conidial survival (Rosa et al., 2000). Otherwise, shaded environment conditions result in an increased humidity and it is known that the percentage of BB infection increases with higher humidity (Shipp et al., 2003).
The shade provided by trees could be expected to reduce CBB infestation, according to previous studies (Jaramillo et al., 2009; Jonsson et al., 2015; Villarreyna and Avelino, 2016; Atallah et al., 2018). Significant differences of CBB infestation were not found

Figure 40. Relation between microclimatic factors, shelter trees and *Hypothenemus hampei* populations:
Effect of shelter trees on microclimatic factors (temperature, RH, wind speed, rainfall impact (< 5 mm), size of raindrops (> 5 mm), dew and solar radiation), and of these microclimatic factors on *Hypothenemus hampei populations* (population increase, dispersion, fruit emergence, fertility, longevity).



(Source: Villarreyna and Avelino, 2016)

between shading methods, since the shade within the plots assessed was not uniform. Obviously, there were zones within the plots subject to direct sunlight despite the presence of shelter trees. The shelter trees were not developed enough to provide a uniform shade within the plots and consequently generate all their known impact on CBB infestation (**Erreur ! Source du renvoi introuvable.**). These small sun-exposed patches could favour CBB activity, since the temperature is higher there (Jaramillo et al., 2009).

7.3 Colletotrichum spp. incidence and severity

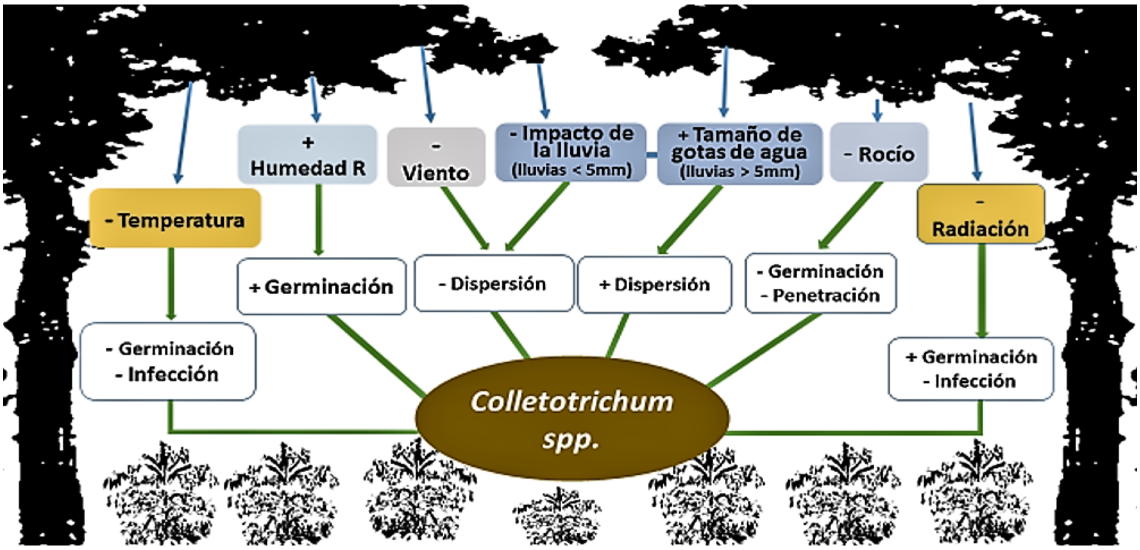
Although significant results have not be found for the response variable of CS incidence, it is worth noting that CS incidence was quite high in July, i.e. above the economic threshold, and very low in August and September, i.e. below the economic threshold. CS spreads by means of water-born conidia, their maximum growth occuring within a pH range of 6.5-7 and a temperature range of 25°C-30°C; conidia germinate at relative humidities between 95%-100% (Jeffries et al., 1990; Dodd et al., 1991; Hubballi et al., 2011). According to Table 7, in mid-July, CS incidence was above the economic threshold, due to a very favourable climate for fungus in June, with a relative humidity (RH) of 95% at 7 am allowing the conidia to germinate. In June the mean maximum temperature did not exceed 30°C, another factor contributing to a better growth of CS. CS incidence decreased significantly in August, after the mean maximum temperature had exceeded 30°C in July and no mean RH ever reached 95%. The decrease continued in September, after the temperature had been above 30°C in August, it rained less (150.7 mm) and the RH slightly dipped in comparison with July. The dryer climate in August could explain why CS incidence was very low in September.

Regarding CS severity, although the rates obtained were not a significant problem on the whole, it is interesting to point out and explain why IO plots showed a higher CS severity than the other farming practice plots. Firstly, CS does not seem to affect the yield, since IO plots yielded the most (Figure 36) while showing the highest CS severity among all the farming practices. A possible explanation could be that sensitivity to CS increases with the fruit load, since an important fruit load can cause nutrient imbalance inside the plant. This fact has been pointed out by Carvalho et al., (2001) with CLR: the coffee plants' susceptibility to CLR is more pronounced when the fruit load is higher. It can therefore be hypothesised that susceptibility to CS severity of Robusta coffee plants cultivated in an IO farming practice increases, since IO plots yield more than the others. The same fact was observed in the present study and discussed above with respect to BTB infestation (section 7.1).

Another explanation accounting for these results could be that the type of Robusta coffee genotype causes significant variations of susceptibility to CS severity. Indeed, 2 Robusta clones were planted in every plot, NP-3013 and NP-2024. It is possible that a majority of the plants selected for the present trial located in IO plots belonged to either NP-3013 or

NP-2024, and that this particular majority happened to be less resistant to CS disease. Further research is needed to support or refute this hypothesis.

Figure 41. Relation between microclimatic factors, shelter trees and *Colletotrichum spp.* development:
Effect of the shelter trees on microclimatic factors (temperature, RH, wind speed, rainfall impact (< 5 mm), size of raindrops (> 5 mm), dew and solar radiation) and of these microclimatic factors on *Colletotrichum spp*. development (dispersion, germination, penetration, infection).



(Source: Villarreyna and Avelino, 2016)

Interestingly, although no significant differences were found between shading methods for both CS incidence and severity, it can be pointed out that in July CS incidence was higher in coffee plots with shelter trees than those without, whereas this tendency was opposite for CS severity, which seemed to be the highest within the full sun coffee plots. The analysis of the impact of microclimatic factors on CS development, led by Villarreyna-Acuña and Avelino (2016), shows that shelter trees have a mild negative effect on both penetration and infection by CLS fungus (**Erreur ! Source du renvoi introuvable.**). The drawback of this representation is that it takes no account of altitude, which can change the microclimate and therefore CS incidence and severity (Matovu et al., 2013). A higher CS incidence in shaded plots was probably found because the shaded systems increased RH, thus presenting more suitable fungal growing conditions. The temperature was optimal for fungal growth under shaded conditions, since the mean maximum temperature in July was 30.3°C. The results achieved for CS severity are in agreement with another study carried out on *Euonymus fortunei* (Ningen et al., 2005). CS severity under shaded conditions is less pronounced than under full sun conditions, while Robusta coffee plants have a better nutrient balance in shaded systems, as detailed in section 7.1. This same section also points out that phenolic compounds are greater in coffee leaves under shaded conditions, a fact that could also explain why CS severity is reduced under shaded conditions.

7.4 *Cercospora coffeicola* incidence

Although no significant results were obtained, both Figure 23 and 24 indicate an increase of CLS incidence in August only. One explanation could be that the number of leaves on coffee plants was reduced in August, following a high CS incidence in July that induced leaves to drop in an important way. The reduced number of leaves remaining in August could have heightened CLS incidence, this last variable being related to the total number of leaves. It could also be suggested that CLS fungus grows better in a humid and very warm environment and thus its incidence is higher in August than in July, since the month of August was dryer than July with a respectively mean maximum temperature of 30.7°C and 30.3°C and a mean daily rainfall of 5.4 mm and 7.3 mm, according to Table 7. CLS and CS fungi do not have the same environment, especially for conidial germination. In September, CLS incidence decreased because RH was not high enough to keep the fungus growing, CLS fungus also needing highly humid conditions (Rengifo et al., 2002). The fact that in August the CLS incidence rate was higher in IC plots could be due to a supposed lack of nutrients, as previously explained in section 7.1. As demonstrated by Rengifo et al. (2002), a lack of nutrients could lead to greater susceptibility to CLS fungus, which thrives better on young leaves.

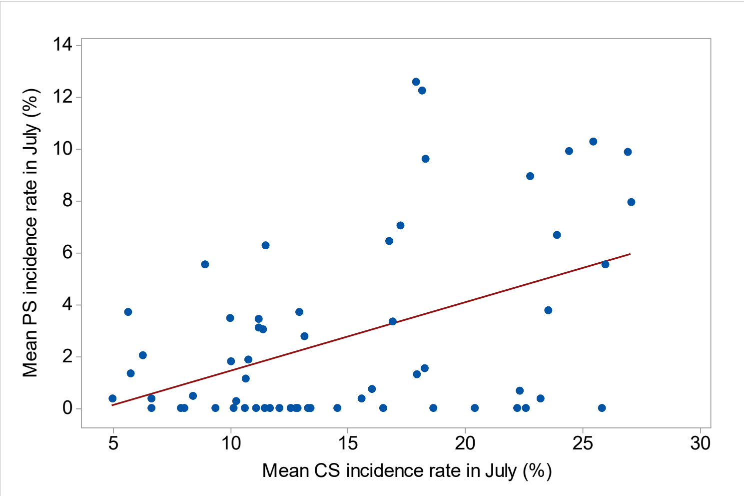
Although shade has been reported as reducing CLS incidence for the reason that the fungus produces cercosporin, a photoactive toxin considered to be an aggressiveness factor (Souza et al., 2015), any impact of shade on CLS incidence cannot be pointed out by the results achieved in the present study. A possible factor that may have led to these results is the insufficient development of shelter trees, unable to provide sufficient shade and reveal their benefits.

7.5 *Phoma spp.* incidence

Whereas the results achieved were not statistically significant, it is worth noting that PS incidence was highest in July, the same occurring with CS incidence. Both fungi have similar growth conditions (Lorenzetti et al., 2015) and their foliar symptoms being able to amalgamate, this can lead to confusion, as observed in the field (**Erreur ! Source du renvoi introuvable.**). CS symptoms were identified as anthracite leaf necrosis, rough to the touch, crisp and non-shiny whereas PS symptoms were identified as a coffee-coloured necrosis, smooth to the touch and shiny. It is very likely that during evaluation a confusion of symptoms between these 2 fungal diseases led to finding no significant differences between shading method and farming practices.

PS incidence was the greatest in July because it may be correlated with CS incidence, which was also higher in July than in the other months assessed. There is a positive correlation between the PS and CS incidence rates. That is the correlation highlighted in **Erreur ! Source du renvoi introuvable.** it is statistically significant with a p-value < 0.001.

Figure 42. Correlation between the mean incidence rates in July of *Phoma spp.* and *Colletotrichum spp.*
The regression line is figured in red.



7.6 *Pellicularia koleroga* incidence

Although, as mentioned above in section 1.4.3, Robusta coffee is more susceptible to TB than Arabica coffee, the achieved results indicate that TB is not a problematic disease, due to the weather being too hot in EAR for TB to develop (Waller et al., 2007).

7.7 *Leucoptera coffeella* infestation

The results achieved were not all statistically significant. It is nonetheless worth noting that the CLM infestation rate was higher in July than in August and September, a fact possibly explained by the leaf miner incidence being favoured in July by higher rainfall; Lomeli et al., (2009, 2010) reports that leaf miner incidence is higher during rainy seasons. Pereira et al. (2007a) pointed out that the mortality of CLM larvae amounted to about 33.7% during the rainy season and to about 61% during the dry season, probably because the Vespidae predators of CLM larvae are more active during the dry season (Pereira et al., 2007b). The slightly dryer climate in August and September could have contributed to markedly reducing the leaf miner incidence. Another factor that could support this difference is that during the month of July, CS and PS incidence rates were also greater than during the other months. It is therefore likely that part of the mining damage occured on the same leaves as those damaged by CS and/or PS, as shown in **Erreur ! Source du renvoi introuvable.**. In this way, leaves dropping to the ground due to high CS and/or PS severity may also reduce the number of leaves damaged by leaf miners.

It is also worth outlining that CLM infestation rates were greater in IC plots in July and August. As previously detailed in section 7.1, the fact that Robusta coffee plants grown according to conventional farming practices are subject to either lack or imbalance of nutrient, could be responsible for this; it is reported that plants containing higher levels of sugar and protein are more resistant to CLM (Martarello et al., 2009). In other words, Robusta coffee plants with low N levels are probably less resistant to CLM.

7.8 Shade percentages

Using a pyranometer revealed that the mean daily shade percentages of the plots applying the SUN, TaE, TIM, GUA and ERY shading methods were respectively: 0.6%, 9.2%, 15.1%, 26.4% and 29.8%. The temporary *Musa spp*. shade must be included in these percentages and consequently, when the *Musa spp*. plants are cut down, these shade percentages will be lower, except for that of the SUN shading method. In this respect, the latter could be viewed as insufficient, at least in providing a negative effect on CBB infestation, which requires an approximate 25% shade value (Atallah et al., 2018). In the present trial, there have been few significant results regarding the impact of shade on PDD, mainly due to the shade not being uniform within the assessed plots, as indicated by Table 32.

Table 32: Shade quantity in % per plant for each shading method. Data were provided by the pyranometer between 9am-10.30am

Shading method	***Shade quantity per coffee plant (%)***							
SUN	0	0	0	1	2	2	2	3
TIM	0	0	0	0	0	0	1	2
	2	15	16	19	24	28	49	80
TaE	0	0	0	0	0	0	0	0
	1	1	1	1	2	2	2	3
	3	5	14	15	16	18	18	18
	18	24	38	70				
GUA	0	0	1	1	13	14	16	17
	18	36	40	49	51	51	58	61
ERY	0	0	1	3	16	29	32	32
	34	35	39	59	61	72	78	82

Shelter trees and coffee plants were planted on 20.11.2015 and IE trees were replanted on 24.07.2017. All trees and plants were three years old, except for the one-year-old IE tree. Clearly, the trees were not fully developed and unable to provide substantial shading, in addition to the MB trees having suffered too much pruning to grow well, and their naturally slow growth. Table 13 shows that MB are very small and cannot provide any notable shade, barely covering one fifth of the side of Robusta coffee plants (**Erreur ! Source du renvoi introuvable.**). Thus, MB trees did not remarkably contribute to the shade percentage of the shading method and, because many of them were either too small (< 1m high) or dead, the banana trees became greater shade providers (**Erreur ! Source du renvoi introuvable.**). In fact, along with the TIM shading method, the banana trees were the main contributors of the shade covering the plot. The same tendency appears in the TaE shading method, where the density of MB trees is 41.5 plants/ha, whereas it is 83 plants/ha in the TIM shading method. In the TaE shading method, MB trees could not provide shade to the experimental unit, because of its very low density, low height and crown diameter (Table 9). As to the ES trees within TaE plots, the shade they provided accounted for about 3.7%, since the ERY shading method counted about 333 plants/ha for a 29.8% shade percentage, also meaning that the shade provided by banana trees can be estimated as between 5.5% and 15.1%. This estimation must be confirmed by repeating all the pyranometer measurements after the banana trees have been cut down. Banana trees provide varying amounts of shade owing to the different heights of the trees and to the number of leaves on a tree, which is governed by the pests and diseases thriving on them. Banana trees cannot significantly influence the amount of shade received by Robusta coffee plants, since banana trees are mostly smaller than IE and ES trees and situated below them as shown in Picture 12 and **Erreur ! Source du renvoi introuvable.**.

Although shade percentage between the GUA and ERY shading methods does not significantly differ, it is worth noting that the ERY shading method presents a slightly higher shade percentage than the GUA. This could be explained by the higher tree density in the ERY shading method (333 plants/hectare) than in the GUA (83 plants/hectare). However, with 4 times more trees, the ERY shading method could be expected to present a shade percentage much higher than 29.8%. The heterogeneous development of ERY within the surveyed area could be responsible for this, as figured in **Erreur ! Source du renvoi introuvable.**, as well as the ES tree that is is alternately pruned at 2 m, meaning that half of the trees within the plot deliver less shade to coffee plants, as detailed in Table 8.

The IE tree is interesting, since it provides almost the same shade percentage as the ES tree but with a plantation density 4 times lower than the ES one. Using it would reduce pruning maintenance. Analysing canopies in **Erreur ! Source du renvoi introuvable.** shows that the densest canopy is provided by MB, followed by ES and IE. The ES tree canopy presents large and thick leaves, providing dark shade in sunny conditions. The IE tree canopy presents tapered, disordered leaves providing a rather soft shade.

8. Technical recommendations

The present trial and its results leads to several technical recommendations for future assessments. With respect to PDD evaluation, especially when assessing the CBB infestation rate, it would be better to pick the same number of fruits from each coffee branch, to prevent the fruit load from impacting the CBB infestation rate. Several factors can cause fruit numbers to fluctuate, for instance harvesting, a disease causing the fruit to drop, etc. Harvesting all the fruit from all the Robusta coffee plants in each experimental unit and sampling 100 cherries 4-5 times, would provide the optimal results; CBB infestation would then be evaluated on these cherry lots. When assessing PDD, it would be better to pick the first 8 leaves from a branch in the low part of the coffee plant, the first 10 leaves from a branch in the middle part of the coffee plant and the first 7 leaves from a branch of the upper part of the coffee plant, and always begin the count at the tip of the branches. This would avoid any inaccuracy when identifying the short internode, in addition to the fact that there are no obvious short internodes on branches from the tree's upper part.

For a better understanding of PS and CS growth conditions, identifying the species of both fungi mentioned with molecular markers would be useful, for it is possible that a mix of several fungi species is present. In addition, cultivating the fungi species and infecting healthy coffee plants would give a clearer picture of the epidemiology of both the fungi mentioned under EAR environmental conditions.

As regards farming practices, the use of a green ground cover should be better monitored, since repeated applications of chemical herbicides in the EAR environmental conditions where erosion levels are high, is not recommended; neither is the use of contact herbicides such as paraquat (prohibited in the EU) in the high RH, temperature and rainfall conditions of the EAR. A systemic herbicide would be better suited to these conditions, if only to reduce the number of treatments in a year. It is also important to vary herbicides and their courses of action to prevent resistant weeds from developing. Finally, further research is needed to evaluate the potential use of systemic herbicides applied under the rows only and not between them. On the same topic, all weeds have to be identified to find out if they all really have a negative impact on Robusta coffee plant growth. According to the yields and PDD results, this does not seem to be the case.

Concerning the evaluation of shade under the different AFS, the density of shade trees is to be globally higher to reduce the sunny patches within the experimental shaded area. Further evaluations with the pyranometer should be performed in 2 or 3 years when the trees will be providing constant shade throughout the day. It would also be better to have the same tree density for all treatments at the start and remove the trees later to regulate the shade, otherwise waiting at least another 5 years will be necessary before measuring is begun. At the beginning of the field experiment, plantation density should be at least 333 plants/hectare for all shade trees. Providing shade with banana trees is not recommended since their large and opaque leaves greatly reduce the light available to coffee plants, and when the bananas are ripe they easily drop on the coffee plants and damage them. Lastly, since banana plants are subject to CS (Hindorf, 2000), it is worth investigating whether or not they can heighten CS incidence and severity in coffee plants.

Conclusion and prospects

The field experiment carried out outlines the relevance of coffee AFS in providing a sustainable solution for coffee growers around the world, with particular emphasis on the Amazon region. Specifically, the present study demonstrates that incorporating IE trees to the coffee field at a density of 83 trees/ha allows to significantly reduce up to 9% of the BTB infestation, as compared to Robusta coffee plants fully exposed to the sun in August. This effect could be more readily attributable to the type of tree than the amount of shade it provides (26.4%). Regarding the other response variables (CBB infestation, BB presence, CS incidence and severity, PS incidence, TB incidence and CLM infestation), no significant results appeared when the shading methods were compared, since the shade quantity provided by the shelter trees was probably not sufficient for the coffee agroecosystem and its microclimate to be notably impacted.

Coffee plantations, among other tropical crops such as cocoa, are particularly vulnerable to climate change, in addition to the fluctuating value of coffee. Coffee AFS combined with an adequate farming practice reduce the need for inputs by favouring ecosystem services and improve coffee farmers' livelihood. Nonetheless, AFS need to be promoted by public incentive policies that will provide financial support to coffee farmers and encourage them to make this transition. In the present study, the results achieved show that farming practices did not interact with shading methods. However, the farming practices significantly impacted PDD on Robusta coffee. Conventional farming practices were found to heighten BTB (2%-12% more) and CBB (up to 7 times more) infestation, as compared to organic farming practices. This could be due to the use of synthetic herbicides and fertilisers in conventional farming practices that probably impacted soil fertility, the nutrient balance of plants and the dynamics of natural enemy populations. CS severity was found to be slightly higher in organic plots, probably owing to a reduced quantity of phenolic compounds in the leaves, most of these compounds being in the cherries. Because intensive organic coffee plots yielded more than other farming practices, Robusta coffee leaves may have been less protected in intensive organic plots. According to these results, it is advisable to combine the shading method with an organic farming practice.

This thesis also shows the complexity of coffee AFS. It is not obvious that combining trees with coffee plants is useful in improving coffee crop management. The specific case of coffee PDD requires that several factors be taken into account, such as topography, altitude, climate, microclimate, genotype, all of which can vary the impact of shade on coffee PDD. For instance this study shows that the IE shelter tree had significant impact in August only, suggesting that the impact of shelter trees could be more pronounced during the dry season. The reader should also bear in mind that AFS are not primarily aimed at suppressing all coffee pests and diseases but at enhancing biological interaction to keep them at an acceptable economic threshold. Clearly, as shown in section 6.10 of the present study, the use of shelter trees impacted the coffee cherry yield negatively, a fact explained by a decreasing photosynthetic radiation reaching the coffee plants. However, AFS cannot be considered as a disincentive when Robusta coffee plants yield less in shaded conditions. The economic profitability of AFS has to be considered as a whole. On one hand, AFS may certainly provide a lower cherry yield but on the other hand, must be taken into account the fact that shelter trees provide marketable commodities (such as the IE fruit) and could allow for weeds to be reduced, as well as the costs of pest and disease control, not to mention sustainably perpetuating the coffee agroecosystem. This fact has been demonstrated in El Salvador with an Arabica coffee plantation under MB shade. The yield losses of cherries were offset by the MB resin extraction (Anderson, 2012).

The field experiment presented in this thesis may contribute a response to an important gap in our knowledge of how shade impacts Robusta coffee PDD. Further research is needed to assess the interaction between shelter trees and the pests or diseases affecting Robusta coffee plants. All the results obtained will have to be confirmed by performing the same experiment in 2 or 3 years, when the trees will be more developed: the coffee plants will have begun to bear fruit (3 years) and shelter trees will be between one and three years old. More investigation is required to determine the type of interaction between PS and CS that will improve the control strategy.

Quantifying the amount of shade for each shading method was part of the experiment here described and, allowing for the fact that a certain amount of solar radiation does get through the shelter trees to the coffee plants, the highest shade quantity was given by ES trees with a daily mean of 29.8%. Considering the significant results obtained, the optimal shade level needed to provide better PDD control could be higher; however, field measurements with a pyranometer are opening up new approaches to modeling the interaction between amount-of-solar-radiation and PDD-activity, and finding the optimal value. A trade-off model combining solar radiation-yield-PDD activity could even be found, resulting in the highest possible yield where pest infestation, disease incidence and severity are below the economic threshold.

Clearly, the conclusions of such a trial can be linked to other field assessments such as Shannon's biodiversity index, carbon sequestration rate, soil quality, with the aim of more thoroughly evaluating the impact of shade on Robusta coffee. These field assessments will be carried out by the EECA.

The experiment is limited by site-specific conclusions, potentially applicable to the Amazon region only. Consequently, the optimal shade quantity could be different in regions under other climates. Therefore, coffee AFS research needs to be carried out in a wide range of trials.

References

Abbas, M.A. (1986). Observation on damage by *Xylosandrus compactus* in coffee [*Coffea*] as affected by shade and variety [in Peninsular Malaysia]. MARDI Res. Bull. Malays. *14*, 108–110.

Alves, V., Goulart, F.F., Jacobson, T.K.B., Filho, R.J.M., and Ribas, C.E.D.C. (2016). Shade's benefit: coffee production under shade and full sun. J. Agric. Sci. *8*, 11–19.

Anderson, E. (2012). The impact of balsamo (*Myroxylon balsamum* L. Harms) on coffee yield and household income in El Balsamar, El Salvador. Master's Thesis. Michigan Technological University.

Androcioli, H.G., Morais, H., Júnor, A.O.M., Hoshino, A.T., Androcioli, L.G., and Caramori, P.H. (2015). Cercosporiose progression in the agroforestry consortium coffee-rubber trees. Semina Ciênc. Agrár. *36*, 3647–3656.

Armbrecht, I., and Gallego, M.C. (2007). Testing ant predation on the coffee berry borer in shaded and sun coffee plantations in Colombia. Entomol. Exp. Appl. *124*, 261–267.

Atallah, S.S., Gómez, M.I., and Jaramillo, J. (2018). A Bioeconomic Model of Ecosystem Services Provision: Coffee Berry Borer and Shade-grown Coffee in Colombia. Ecol. Econ. *144*, 129–138.

Augspurger, C.K. (1984). Seedling Survival of Tropical Tree Species: Interactions of Dispersal Distance, Light-Gaps, and Pathogens. Ecology *65*, 1705–1712.

Avelino, J., Muller, R.A., Cilas, C., and Velasco, H.P. (1991). Développement et comportement de la rouille orangée du caféier (*Hemileia vastatrix* Berk. et Br.) dans des plantations en cours de modernisation, plantées de variétés naines, dans le sud-est du Mexique (Francés traducido integralmente al Español) - Desarrollo y comportamiento de la roya anaranjada del cafeto (*Hemileia vastatrix* Berk. y Br.) en plantaciones en proceso de modernización, cultivadas con variedades de porte bajo en el Sureste de México. Café Cacao Thé *35*, 21–37.

Avelino, J., Cabut, S., Barboza, B., Barquero, M., Alfaro, R., Esquivel, C., Durand, J.-F., and Cilas, C. (2007). Topography and crop management are key factors for the development of american leaf spot epidemics on coffee in costa rica. Phytopathology *97*, 1532–1542.

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A.J., and Morales, C. (2015). The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. Food Secur. *7*, 303–321.

Babbar, L.I., and Zak, D.R. (1995). Nitrogen Loss from Coffee Agroecosystems in Costa Rica: Leaching and Denitrification in the Presence and Absence of Shade Trees. J. Environ. Qual. *24*, 227–233.

Baker, P.S., Jackson, J.A.F., and Murphy, S.T. (2002). Natural enemies, natural allies. How scientists and coffee farmers forged new partnerships in the war against pests and low prices. (Egham, UK: CABI Commodities).

Barrance, A., Beer, J., Boshier, D.H., Chamberlain, J., Cordero, J., Detlefsen, G., Finegan, B., Galloway, G., Gómez, M., Gordon, J., et al. (2003). *Inga edulis* Mart. In Árboles de Centroamérica: un manual para extensionistas, (United Kingdom, Costa Rica: Jesús Cordero, David Boshier), pp. 605–606.

Barrera, J.F. (2002). El Taladrador de las Ramas del café Robusta: la otra Broca del café. In Tres plagas del café en Chiapas, (Mexico: Juan F. Barrera), pp. 81–84.

Bedimo, J.A.M., Bieysse, D., Nyassé, S., Nottéghem, J.L., and Cilas, C. (2010). Role of rainfall in the development of coffee berry disease in *Coffea arabica* caused by *Colletotrichum kahawae*, in Cameroon. Plant Pathol. *59*, 324–329.

Bedimo, J.A.M., Dufour, B.P., Cilas, C., and Avelino, J. (2012). Effets des arbres d'ombrage sur les bioagresseurs de *Coffea arabica*. Cah. Agric. *21*, 89–97.

Bedimo, J.M., Njiayouom, I., Bieysse, D., Nkeng, M.N., Cilas, C., and Nottéghem, J.-L. (2008). Effect of shade on Arabica coffee berry disease development: toward an agroforestry system to reduce disease impact. Phytopathology *98*, 1320–1325.

Beer, J., Muschler, R., Kass, D., and Somarriba, E. (1997). Shade management in coffee and cacao plantations. Agrofor. Syst. *38*, 139–164.

Benavides, G.M. (1961). El *Xyleborus morigerus* Blandford en Colombia. Cenicafé *12*, 17–28.

Bertrand, B., Aguilar, G., and Santacreo, R. (1999). El Mejoramiento Genético en América Central. In Desafíos de La Caficultura En Centroamérica, (San Jose, Costa Rica: Benoît Bertrand y Bruno Rapidel), pp. 407–456.

Bertrand, B., Alpizar, E., Lara, L., SantaCreo, R., Hidalgo, M., Quijano, J.M., Montagnon, C., Georget, F., and Etienne, H. (2011). Performance of *Coffea arabica* F1 hybrids in agroforestry and full-sun cropping systems in comparison with American pure line cultivars. Euphytica *181*, 147–158.

Boreux, V., Vaast, P., Madappa, L.P., Cheppudira, K.G., Garcia, C., and Ghazoul, J. (2016). Agroforestry coffee production increased by native shade trees, irrigation, and liming. Agron. Sustain. Dev. *36*, 42.

Bosselmann, A.S., Dons, K., Oberthur, T., Olsen, C.S., Ræbild, A., and Usma, H. (2009). The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agric. Ecosyst. Environ. *129*, 253–260.

Boudrot, A., Pico, J., Merle, I., Granados, E., Vílchez, S., Tixier, P., Filho, E.M.V., Casanoves, F., Tapia, A., Allinne, C., et al. (2016). Shade Effects on the Dispersal of Airborne *Hemileia vastatrix* Uredospores. Phytopathology *106*, 572–580.

Bruck, D.J., and Lewis, L.C. (2002). Rainfall and crop residue effects on soil dispersion and *Beauveria bassiana* spread to corn. Appl. Soil Ecol. *20*, 183–190.

Brun, L.O., Marcillaud, C., Gaudichon, V., and Suckling, D.M. (1989). Endosulfan resistance in *Hypothenemus hampei* (Coleoptera : Scolytidae) in New Caledonia. J. Econ. Entomol. *82*, 1311–1316.

Bukomeko, H., Jassogne, L., H. Kagezi, G., Mukasa, D., and Vaast, P. (2017). Influence of shaded systems on *Xylosandrus compactus* infestation in Robusta coffee along a rainfall gradient in Uganda: Shaded coffee systems and *X. compactus*. Agric. For. Entomol. *20*, 327–333.

Bunn, C., Läderach, P., Rivera, O.O., and Kirschke, D. (2015). A bitter cup: climate change profile of global production of Arabica and Robusta coffee. Clim. Change *129*, 89–101.

Bustillo, A.E., Cárdenas, R., and Posada, F.J. (2002). Natural enemies and competitors of *Hypothenemus hampei* (Ferrari) (Coleoptera: Scolytidae) in Colombia. Neotrop. Entomol. *31*, 635–639.

CAB International (1996). *Mycena citricolor* [Distribution map] (Wallingford, UK: CAB International).

Calderón, G.A.E., Guambi, L.A.D., and Villafuerte, W.P.C. (2014). Germoplasma de café robusta. In Guía técnica para la producción y poscosecha del café, (Portoviejo, Ecuador: Gustavo Adolfo Enríquez Calderón, Luis Alberto Duicela Guambi), pp. 27–45.

Campanha, M.M., Santos, R.H.S., Freitas, G.B. de, Martinez, H.E.P., Garcia, S.L.R., and Finger, F.L. (2004). Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais, Brazil. Agrofor. Syst. *63*, 75–82.

Cañarte, E., Navarrete, J., Mendoza, A., Pico, J., Fernández, F., Guerrero, H., Plaza, L., Quijano, J., Párraga, J., Subía, C., et al. (2016). Características sanitarias. In

Mejoramiento y homologación de los procesos y protocolos de investigación, validación y producción de servicios en cacao y café, (Mocache, Ecuador), pp. 41–46.

Cannell, M.G.R., Noordwijk, M.V., and Ong, C.K. (1996). The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agrofor. Syst. *34*, 27–31.

Carvalho, V.D., Chalfoun, S., Castro, H.D., and Carvalho, V.D. (2001). Influência de diferentes níveis de produção sobre a evolução da ferrugem do caffeeiro e sobre teores foliares de compostos fenólicos. Ciênc. E Agrotecnologia *25*, 49–54.

Castro, A.M., Tapias, J., Ortiz, A., Benavides, P., and Góngora, C.E. (2017). Identification of attractant and repellent plants to coffee berry borer, *Hypothenemus hampei*. Entomol. Exp. Appl. *164*, 120–130.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C.A., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N., and Avelino, J. (2017). Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. *82*, 308–319.

Chang, E.-H., Chung, R.-S., and Tsai, Y.-H. (2007). Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. Soil Sci. Plant Nutr. *53*, 132–140.

Clifford, M.N., and Willson, K.C. (1985). Coffee : botany, biochemistry and production of beans and beverage (London: M. N. Clifford and K. C. Wilson).

Cristóbal, F.C., and Mario, F.J. (1998). Plantaciones clonales de café robusta en sistemas agroforestales para la Amazonía Ecuatoriana (Francisco de Orellana: INIAP - EECA).

Custódio, A.A.P., Pozza, E.A., Guimarães, S.S.C., Koshikumo, E.S.M., Hoyos, J.M.A., and Souza, P.E. (2011). Comparison and validation of diagrammatic scales for brown eye spots in coffee tree leaves. Ciênc. E Agrotecnologia *35*, 1067–1076.

Dagnelie, P. (2012). Principes d'expérimentation. Planification des expériences et analyse de leurs résultats (Les Presses Agronomiques de Gembloux, A.S.B.L.).

DaMatta, F.M. (2004). Ecophysiological constraints on the production of shaded and unshaded coffee: a review. Field Crops Res. *86*, 99–114.

DaMatta, F.M., and Ramalho, J.D.C. (2006). Impacts of drought and temperature stress on coffee physiology and production: a review. Braz. J. Plant Physiol. *18*, 55–81.

DaMatta, F.M., Ronchi, C.P., Maestri, M., and Barros, R.S. (2007). Ecophysiology of coffee growth and production. Braz. J. Plant Physiol. *19*, 485–510.

Damon, A. (2000). A review of the biology and control of the coffee berry borer, *Hypothenemus hampei* (Coleoptera: Scolytidae). Bull. Entomol. Res. *90*, 453–465.

Davis, A., Govaerts, R., Bridson, D.M., and Stoffelen, P. (2006). An annotated taxonomic conspectus of genus *Coffea* (Rubiaceae). Bot. J. Linn. Soc. *152*, 465–512.

Déchamp, E., Breitler, J.-C., Leroy, T., and Etienne, H. (2015). Coffee (Coffea arabica L.). In Agrobacterium Protocols, (Springer, New York, NY), pp. 275–291.

Descroix, F., and Snoeck, J. (2012). Environmental Factors Suitable for Coffee Cultivation. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 168–181.

Di Rienzo, J., Macchiavelli, R., and Casanoves, F. (2011). Modelos Lineales Mixtos. Aplicaciones en InfoStat (Córdoba: Grupo Infostat).

Dodd, J.C., Estrada, A.B., Matcham, J., Jeffries, P., and Jeger, M.J. (1991). The effect of climatic factors on *Colletotrichum gloeosporioides*, causal agent of mango anthracnose, in the Philippines. Plant Pathol. *40*, 568–575.

Egonyu, J.P., Baguma, J., Ogari, I., Ahumuza, G., and Ddumba, G. (2017). Host preference by the twig borer *Xylosandrus compactus* (Coleoptera: Scolytidae) and simulated influence of shade trees on its populations. Int. J. Trop. Insect Sci. *37*, 183–188.

Ehrenbergerová, L., Kučera, A., Cienciala, E., Trochta, J., and Volařík, D. (2017). Identifying key factors affecting coffee leaf rust incidence in agroforestry plantations in Peru. Agrofor. Syst. 1–15.

Eskes, A.B., and Leroy, T. (2012). Coffee Selection and Breeding. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 61–90.

ESPAC (2017). Superficie, producción y ventas, según región y provincia. Café (grano oro).

Estívariz, J., and Muschler, R. (1998). Efecto de la sombra sobre el vigor y producción de *Coffea arabica* var. Caturra después de una poda total del café en Turrialba, Costa Rica. Agroforestería Las Am. *5*, 49–53.

Feil, R. (2011). Coffea. Genus, Species, Varieties (Raimond Feil).

Ferwerda, F.P. (1948). Coffee breeding in java. Econ. Bot. *2*, 258–272.

Fragoso, D.B., Jusselino Filho, P., Pallini Filho, A., and Badji, C.A. (2002). Action of Organophosphate Insecticides Used to Control Leucoptera coffeella (Guérin-Mèneville) (Lepidotera: Lyonetiidae) on the Predator Mite Iphiseiodes zuluagai Denmark & Muma (Acari: Phytoseiidae). Neotrop. Entomol. *31*, 463–467.

Franco, H.D.M. (2013). Epidemiologia de la muerte descendente del cafeto (*Phoma sp.*) en cuatro sistemas de producción en la Estación Experimental El Tambo del departamento del Cauca. Magister. Universidad Nacional de Colombia.

Gaitán, A.L., Cristancho, M.A., Castro Caicedo, B.L., Rivillas, C.A., and Gómez, G.C. (2016). Compendium of coffee diseases and pests (Minnesota, USA: The American Phytopathological Society).

Gautam, A.K. (2014). *Colletotrichum gloeosporioides*: Biology, Pathogenicity and Management in India. J. Plant Physiol. Pathol. *2*, 1–11.

Geromel, C., Ferreira, L.P., Davrieux, F., Guyot, B., Ribeyre, F., Brígida dos Santos Scholz, M., Protasio Pereira, L.F., Vaast, P., Pot, D., Leroy, T., et al. (2008). Effects of shade on the development and sugar metabolism of coffee (*Coffea arabica* L.) fruits. Plant Physiol. Biochem. PPB *46*, 569–579.

Giordanengo, P., Brun, L.O., and Frerot, B. (1993). Evidence for allelochemical attraction of the coffee berry borer, *Hypothenemus hampei*, by coffee berries. J. Chem. Ecol. *19*, 763–769.

Greco, E.B., and Wright, M.G. (2015). Ecology, Biology, and Management of *Xylosandrus compactus* (Coleoptera: Curculionidae: Scolytinae) with Emphasis on Coffee in Hawaii. J. Integr. Pest Manag. *6*.

Gutiérrez, A.M., and Ondarza, R.N. (1996). Kairomone Effect of Extracts from *Coffea canephora* over *Hypothenemus hampei* (Coleoptera: Scolytidae). Environ. Entomol. *25*, 96–100.

Haggar, J., Barrios, M., Bolaños, M., Merlo, M., Moraga, P., Munguia, R., Ponce, A., Romero, S., Soto, G., Staver, C., et al. (2011). Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. Agrofor. Syst. *82*, 285–301.

Hindorf, H. (2000). *Colletotrichum spp.* causing anthracnose of tropical crops. Acta Hortic. 275–282.

Holdridge, L.R., and Tosi, J.A. (1967). Life zone ecology (San Jose: Tropical Science Center).

Hubballi, M., Nakkeeran, S., Raguchander, T., Anand, T., and Renukadevi, P. (2011). Physiological characterisation of *Colletotrichum gloeosporioides*, the incitant of anthracnose disease of noni in India. Arch. Phytopathol. Plant Prot. *44*, 1105–1114.

ICAFE (2011). Guía Técnica para el Cultivo del Café (Heredia-Costa Rica: ICAFE-CICAFE).

ICO (2016). International Coffee Organization - The Current State of the Global Coffee Trade | #CoffeeTradeStats.

Illy, A. (2005). Espresso coffee: the science of quality (Amsterdam: Elsevier).

Illy, E. (2002). The complexity of coffee. Sci. Am. *286*, 86–91.

INAMHI (2012). Anuario Meteorológico 2010- Nro. 50.

INAMHI (2018). Datos meteorológicos de la EECA en Joya de los Sachas.

IPCC (2007). Climate Change 2007: impacts, adaptation and vulnerability : contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press).

Jackson, G. (2017). Fact sheet - Coffee thread blight (199).

Jaramillo, J., Borgemeister, C., and Baker, P. (2006). Coffee berry borer *Hypothenemus hampei* (Coleoptera: Curculionidae): searching for sustainable control strategies. Bull. Entomol. Res. *96*, 223–233.

Jaramillo, J., Chabi, A.O., Kamonjo, C., Jaramillo, A., Vega, F.E., Poehling, H.-M., and Borgemeister, C. (2009). Thermal Tolerance of the Coffee Berry Borer *Hypothenemus hampei*: Predictions of Climate Change Impact on a Tropical Insect Pest. PLOS ONE *4*, e6487.

Jaramillo, J., Setamou, M., Muchugu, E., Chabi, A.O., Jaramillo, A., Mukabana, J., Maina, J., Gathara, S., and Borgemeister, C. (2013). Climate change or urbanization? Impacts on a traditional coffee production system in East Africa over the last 80 years. PloS One *8*, e51815.

Jaramillo, M.G., Benavides, P., and Constantino, L. (2015). El pasador de las ramas del café *Xylosandrus morigerus* (Coleoptera: Curculionidae: Scolytinae) (Manizales, Caldas, Colombia: Cenicafé).

Jeffries, P., Dodd, J.C., Jeger, M.J., and Plumbley, R.A. (1990). The biology and control of *Colletotrichum* species on tropical fruit crops. Plant Pathol. *39*, 343–366.

Jonsson, M., Raphael, I.A., Ekbom, B., Kyamanywa, S., and Karungi, J. (2015). Contrasting effects of shade level and altitude on two important coffee pests. J. Pest Sci. *88*, 281–287.

Kagezi, G.H., Kucel, P., Mukasa, D., van Asten, P., Musoli, P.C., and Kangire, A. (2012). Preliminary report on the status and host plant utilization by the Black Coffee Twig Borer, *Xylosandrus compactus* (Eichhoff) (Coleoptera: Curculionidae) in Uganda. In Proceedings of the 24th International Conference on Coffee Science (ASIC), (San Jose, Costa Rica), pp. 1323–1326.

Karp, D.S., Mendenhall, C.D., Sandí, R.F., Chaumont, N., Ehrlich, P.R., Hadly, E.A., and Daily, G.C. (2013). Forest bolsters bird abundance, pest control and coffee yield. Ecol. Lett. *16*, 1339–1347.

Kass, D.C.L. (1994). Erythrina species-pantropical multipurpose tree legumes. In Forage Tree Legumes in Tropical Agriculture, (Wallingford, UK: Ross C. Gutteridge and H. Max Shelton), pp. 84–96.

Le Pelley, R.H. (1968). Pests of coffee (London: Longmans).

Lemmon, P.E. (1957). A new instrument for measuring forest overstory density. J. For. *9*, 667–669.

Letourneau, D.K., Armbrecht, I., Rivera, B.S., Lerma, J.M., Carmona, E.J., Daza, M.C., Escobar, S., Galindo, V., Gutiérrez, C., López, S.D., et al. (2011). Does plant diversity benefit agroecosystems? A synthetic review. Ecol. Appl. *21*, 9–21.

Liebig, T.I. (2017). Abundance of pests and diseases in Arabica coffee production systems in Uganda-ecological mechanisms and spatial analysis in the face of climate change. Doctorate. Gottfried Wilhelm Leibniz Universität.

Liebig, T., Laderach, P., Quiroga, A., Anzueto, F., Matute, N., and Avelino, J. (2015). Spatial Decision Support for Coffee Disease Management – Site-Specific Shade – Environment Interaction affecting American Leaf Spot Disease. p.

Long, N.V., Ngoc, N.Q., Dung, N.N., Kristiansen, P., Yunusa, I., and Fyfe, C. (2015). The Effects of Shade Tree Types on Light Variation and Robusta Coffee Production in Vietnam. Engineering *07*, 742.

Loor, R.G.S., Bellis, F.D., Leroy, T., Plaza, L., Guerrero, H., Subía, C., Calderón, D., Fernández, F., Garzon, I., Lopez, D., et al. (2017). Revealing the Diversity of Introduced *Coffea canephora* Germplasm in Ecuador: Towards a National Strategy to Improve Robusta. Sci. World J. *2017*, 1–12.

López, D.F.B., Virginio, E.D.M.F., and Avelino, J. (2012). Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Prot. *38*, 21–29.

Lorenzetti, E.R., Pozza, E.A., Souza, P.E. de, Santos, L.A., Alves, E., Silva, A.C. da, Maia, F.G.M., and Carvalho, R.R. da C. (2015). Effect of temperature and leaf wetness on *Phoma tarde* and phoma leaf spot in coffee seedlings.

MAGAP (2017). MAGAP ejecuta “Proyecto de Reactivación de la Caficultura Ecuatoriana” – Ministerio de Agricultura y Ganadería.

Mariño, Y.A., Pérez, M.E., Gallardo, F., Trifilio, M., Cruz, M., and Bayman, P. (2016). Sun vs. shade affects infestation, total population and sex ratio of the coffee berry borer (*Hypothenemus hampei*) in Puerto Rico. Agric. Ecosyst. Environ. *222*, 258–266.

Mariño, Y.A., Vega, V.J., García, J.M., Rodrigues, V., García, N.M., and Bayman, P. (2017). The Coffee Berry Borer (Coleoptera: Curculionidae) in Puerto Rico: distribution, infestation, and population per fruit. J. Insect Sci. *17*, 1–8.

Martarello, F.H.H., Guerreiro, O.F., Salva, T.J.G., and Maluf, M.P. (2009). Biochemical characterization of resistant and susceptible coffee plants to the coffee leaf miner (*Leucoptera coffeella*). In 22nd International Conference on Coffee Science, ASIC 2008, Campinas, SP, Brazil, 14-19 September, 2008, (Campinas, Brazil: ASIC), pp. 1049–1052.

Martínez, H.W.Q., Pérez, R.A.D., and Yanes, H.A.V. (2002). Estudio socioeconómico y agroforestal del bálsamo (*Myroxylon balsamun*) en la Cooperativa Chiquileca Santa Isabel Ishuatán, Sonsonate. Ingeniería. Universidad de El Salvador.

Matovu, R.J., Kangire, A., Phiri, N.A., Hakiza, G.H., Kagezi, G.H., and Musoli, P.C. (2013). Ecological factors influencing incidence and severity of coffee leaf rust and coffee berry disease in major arabica coffee growing districts of Uganda. Uganda J. Agric. Sci. *14*, 87–100.

Medina, H.P.F., Carvalho, A., Sondahl, M.R., Fazuoli, L.C., and Costa, W.M. (1984). Coffee Breeding and Related Evolutionary Aspects. In Plant Breeding Reviews, J. Janick, ed. (Westport, USA: Jules Janick), pp. 157–193.

Mendesil, E., Bruce, T.J.A., Woodcock, C.M., Caulfield, J.C., Seyoum, E., and Pickett, J.A. (2009). Semiochemicals used in Host Location by the Coffee berry Borer, *Hypothenemus hampei*. J. Chem. Ecol. *35*, 944–950.

Meylan, L., Gary, C., Allinne, C., Ortiz, J., Jackson, L., and Rapidel, B. (2017). Evaluating the effect of shade trees on provision of ecosystem services in intensively managed coffee plantations. Agric. Ecosyst. Environ. *245*, 32–42.

Moncada, M.D.P., Tovar, E., Montoya, J.C., González, A., Spindel, J., and McCouch, S. (2016). A genetic linkage map of coffee (*Coffea arabica* L.) and QTL for yield, plant height, and bean size. Tree Genet. Genomes *12*, 1–17.

Montero, M.D.M.G. (2015). Estudio de la epidemiología y alternativas de manejo agroecológico del ojo de gallo (*Mycena citricolor*) en cafeto bajo systemas agroforestales en Costa Rica. Doctorado. Universidad de Costa Rica.

Moreno, J. (2018). Personal communication.

Morris, J., Jimenez, E.S., Philpott, S.M., and Perfecto, I. (2017). Ant-mediated (Hymenoptera: Formicidae) biological control of the coffee berry borer: Diversity, ecological complexity, and conservation biocontrol. Myrmecol. News *26*, 1–17.

Muller, R.A., Berry, D., Avelino, J., and Bieysse, D. (2012). Coffee diseases. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 495–556.

Muschler, R.G. (2012). Shade Management and its Effect on Coffee Growth and Quality. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 395–422.

Nesper, M., Kueffer, C., Krishnan, S., Kushalappa, C.G., and Ghazoul, J. (2017). Shade tree diversity enhances coffee production and quality in agroforestry systems in the Western Ghats. Agric. Ecosyst. Environ. *247*, 172–181.

Nieto, C., and Caicedo, C. (2012). Análisis reflexivo sobre el desarrollo agropecuario sostenible en la Amazonía ecuatoriana (La Joya de los Sachas-Orellana-Ecuador: INIAP - EECA).

Ningen, S.S., Cole, J.C., Smith, M.W., Dunn, D.E., and Conway, K.E. (2005). Increased Shade Intensity and Afternoon Irrigation Decrease Anthracnose Severity on Three *Euonymus fortunei* Cultivars. HortScience *40*, 111–113.

Noordwijk, M.V., Lawson, G., Soumaré, A., Groot, J.J.R., and Hairiah, K. (2015). Root distribution of trees and crops: competition and/or complementarity. In Tree-Crop Interactions: Agroforestry in a Changing Climate, (Malaysia: C. K. Ong and P. Huxley), pp. 319–364.

Nygren, P., Fernandez, M.P., Harmand, J.-M., and Leblanc, H. (2012). Symbiotic dinitrogen fixation by trees: An underestimated resource in agroforestry systems? Nutr. Cycl. Agroecosystems *94*, 123–160.

Ogutu, C., Fang, T., Yan, L., Wang, L., Huang, L., Wang, X., Ma, B., Deng, X., Owiti, A., Nyende, A., et al. (2016). Characterization and utilization of microsatellites in the *Coffea canephora* genome to assess genetic association between wild species in Kenya and cultivated coffee. Tree Genet. Genomes *12*, 1–9.

Ortiz, A., Ortiz, A., Vega, F.E., and Posada, F. (2004). Volatile Composition of Coffee Berries at Different Stages of Ripeness and Their Possible Attraction to the Coffee Berry Borer *Hypothenemus hampei* (Coleoptera: Curculionidae). J. Agric. Food Chem. *52*, 5914–5918.

Palm, C.A., and Sanchez, P.A. (1990). Decomposition and Nutrient Release Patterns of the Leaves of Three Tropical Legumes. Biotropica *22*, 330–338.

Pasiecznik, N. (2014). Myroxylon balsamum (Peru balsam).

Pereira, E.J.G., Picanço, M.C., Bacci, L., Crespo, A.L.B., and Guedes, R.N.C. (2007a). Seasonal mortality factors of the coffee leafminer, *Leucoptera coffeella*. Bull. Entomol. Res. *97*, 421–432.

Pereira, E.J.G., Picanço, M.C., Bacci, L., Lucia, T.M.C.D., Silva, E.M., and Fernandes, F.L. (2007b). Natural mortality factors of *Leucoptera coffeella* (Lepidoptera: Lyonetiidae) on *Coffea arabica*. Biocontrol Sci. Technol. *17*, 441–455.

Perfecto, I., and Vandermeer, J.H. (2015). Coffee agroecology: a new approach to understanding agricultural biodiversity, ecosystem services and sustainable development (London: Routledge).

Philpott, S.M., and Armbrecht, I. (2006). Biodiversity in tropical agroforests and the ecological role of ants and ant diversity in predatory function. Ecol. Entomol. *31*, 369–377.

Pohlan, J., Hermann, A., Janssens, M.J.J., and Eversbusch, B.G. (2008). Impact of Canavalia Cover Crop Management in *Coffea arabica* L. on Plant-Invertebrate Associations. Open Agric. J. *2*, 84–89.

Poudel, D.D., Horwath, W.R., Lanini, W.T., Temple, S.R., and Bruggen, A.H.C.V. (2002). Comparison of soil N availability and leaching potential, crop yields and weeds in organic, low-input and conventional farming systems in northern California. Agric. Ecosyst. Environ. *90*, 125–137.

Pozza, A.A.A., Martinez, P., Emília, H., Caixeta, S.L., Cardoso, A.A., Zambolim, L., and Pozza, E.A. (2001). Influence of the mineral nutrition on intensity of brown-eye spot in young coffee plants. Pesqui. Agropecuária Bras. *36*, 53–60.

Pumariño, L., Sileshi, G.W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M.N., Midega, C., and Jonsson, M. (2015). Effects of agroforestry on pest, disease and weed control: A meta-analysis. Basic Appl. Ecol. *16*, 573–582.

Rengifo, H.G.G., Leguizamón, J.E.C., and Riaño, N.M.H. (2002). Algunos aspectos biológicos de *Cercospora coffeicola*. Cenicafé *53*, 169–177.

Rivillas, C.A.O., and Castro, A.M.T. (2011). Ojo de gallo o gotera del cafeto *Omphalia flavida*. Cenicafé 1–24.

Rodríguez, N.F.L., Martins, S.C.V., Cavatte, P.C., Silva, P.E.M., Morais, L.E., Pereira, L.F., Reis, J.V., Ávila, R.T., Godoy, A.G., Lavinski, A.O., et al. (2014). Morphological and physiological acclimations of coffee seedlings to growth over a range of fixed or changing light supplies. Environ. Exp. Bot. *102*, 1–10.

Root, R.B. (1973). Organization of a Plant-Arthropod Association in Simple and Diverse Habitats: The Fauna of Collards (*Brassica Oleracea*). Ecol. Monogr. *43*, 95–124.

Rosa, W.D.L., Alatorre, R., Barrera, J.F., and Toriello, C. (2000). Effect of *Beauveria bassiana* and *Metarhizium anisopliae* (Deuteromycetes) upon the Coffee Berry Borer (Coleoptera: Scolytidae) Under Field Conditions. J. Econ. Entomol. *93*, 1409–1414.

Rueda, G.D., Constantino, L., Montoya, E.C., Ortega, O.E., Gil, Z.N., and Benavides, P. (2016). Diagnostic of *Leucoptera coffeella* (Lepidoptera: Lyonetiidae) and its parasitoids in the department of Antioquia, Colombia. Rev. Colomb. Entomol. *42*, 4–11.

Rutherford, M., and Phiri, N. (2006). Pests and Diseases of Coffee in Eastern Africa: A Technical and Advisory Manual (Wallingford, UK: Mike Rutherford and Noah Phiri).

Salazar, A., Szott, L.T., and Palm, C.A. (1993). Crop-tree interactions in alley cropping systems on alluvial soils of the Upper Amazon Basin. Agrofor. Syst. *22*, 67–82.

Salgado, B.G., Macedo, R.L.G., and Salgado, M. (2007). Progresso da ferrugem e da cercosporiose do cafeeiro consorciado com grevílea, com injazeiro e a pleno sol em Lavras, MG. Ciênc. E Agrotecnologia *31*, 1067–1074.

Salgado, P.R., Favarin, J.L., Leandro, R.A., Filho, L., and De, O.F. (2008). Total phenol concentrations in coffee tree leaves during fruit development. Sci. Agric. *65*, 354–359.

Sartori, A.L.B., Lewis, G.P., Mansano, V. de F., and Tozzi, A.M.G. de A. (2015). A revision of the genus *Myroxylon* (Leguminosae: Papilionoideae). Kew Bull. *70*, 48.

Sauvadet, M., Meersche, K.V.D., Allinne, C., Gay, F., Filho, E.D.M.V., Chauvat, M., Becquer, T., Tixier, P., and Harmand, J.-M. (2019). Shade trees have higher impact on soil nutrient availability and food web in organic than conventional coffee agroforestry. Sci. Total Environ. *649*, 1065–1074.

Schnabel, F., Filho, E.D.M.V., Xu, S., Fisk, I.D., Roupsard, O., and Haggar, J. (2017). Shade trees: a determinant to the relative success of organic versus conventional coffee production. Agrofor. Syst. 1–15.

Schroth, G., Krauss, U., Gasparotto, L., Aguilar, J.A.D., and Vohland, K. (2000). Pests and diseases in agroforestry systems of the humid tropics. Agrofor. Syst. *50*, 199–241.

Segura, M.B.E. (2017). Efectos de la sombra de cashá (*Chloroleucon eurycyclum*) en el cultivo del café (*Coffea arabica*) sobre los procesos de esporulación, dispersión a través del agua y deposición de *Hemileia vastatrix*, en Turrialba, Costa Rica. Mémoire. CATIE.

SENASICA (2014). Ojo de gallo (*Mycena citricolor* Berkeley) (México: SENASICA (Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria)).

Serna, M.I.Y. (2016). Evaluacion de la incidencia de las enfermedades por factores climaticos y manejo agronomico en zonas cafetaleras de la region de Caranavi. Ingeniería. Universidad Mayor de San Andrés.

Shipp, J.L., Zhang, Y., Hunt, D.W.A., and Ferguson, G. (2003). Influence of Humidity and Greenhouse Microclimate on the Efficacy of *Beauveria bassiana* (Balsamo) for Control of Greenhouse Arthropod Pests. Environ. Entomol. *32*, 1154–1163.

Siles, P., Harmand, J.-M., and Vaast, P. (2010). Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agrofor. Syst. *78*, 269–286.

Silva, N.T.M.H.D., and Tisdell, C. (1990). Evaluating techniques for weed control in coffee in Papua New Guinea. Int. Tree Crops J. *6*, 31–49.

Smith, C. (2015). Bird communities in sun and shade coffee farms in Kenya. Master. Humboldt State University.

Soil Survey Staff (2014). Keys to Soil Taxonomy (Washington, DC: USDA-Natural Resources Conservation Service).

Somporn, C., Kamtuo, A., Theerakulpisut, P., and Siriamornpun, S. (2012). Effect of shading on yield, sugar content, phenolic acids and antioxidant property of coffee beans (*Coffea arabica* L. cv. Catimor) harvested from north-eastern Thailand. J. Sci. Food Agric. *92*, 1956–1963.

Sotomayor, I.A.H. (1993). Enfermedades del Cafeto. In Manual del cultivo del café, (Pichilingue, Ecuador: Sotomayor Herrera Ignacio Antonio), pp. 118–143.

Sousa, K.F.D.D., Detlefsen, G., Filho, E.D.M.V., Tobar, D., and Casanoves, F. (2016). Timber yield from smallholder agroforestry systems in Nicaragua and Honduras. Agrofor. Syst. *90*, 207–218.

Souza, A.G.C., Maffia, L.A., Silva, F.F., Mizubuti, E.S.G., and Teixeira, H. (2015). A time series analysis of brown eye spot progress in conventional and organic coffee production systems. Plant Pathol. *64*, 157–166.

Souza, J.C.D., Reis, P.R., and RIgitano, R.L.D.O. (1998). Bicho-mineiro: biologia, danos e manejo integrado (Brazil: Vânia Lúcia Alves Lacerda).

Stamps, W.T., and Linit, M.J. (1997). Plant diversity and arthropod communities: Implications for temperate agroforestry. Agrofor. Syst. *39*, 73–89.

Staver, C., Guharay, F., Monterroso, D., and Muschler, R.G. (2001). Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agrofor. Syst. *53*, 151–170.

Subía, C., Paredes, N., Caicedo, W., Fernández, F., Díaz, A., Bastidas, F., and Chávez, J. (2014). Análisis socioproductivo de los sistemas de producción agropecuaria en la zona norte y centro de la Amazonía Ecuatoriana. In Agroforestería Sostenible En La Amazonía Ecuatoriana, (Turrialba, Costa Rica: Elias de Melo Virginio Filho, Carlos Estuardo Caicedo Vargas, Carlos Astorga Domian), pp. 48–58.

Thapa, S., and Lantinga, E.A. (2017). Growing Coffee in the Shade: A Strategy to Minimize the Prevalence of Coffee White Stem Borer, *Xylotrechus quadripes*. Southwest. Entomol. *42*, 357–362.

Torquebiau, E.F. (2000). A renewed perspective on agroforestry concepts and classification. Comptes Rendus Académie Sci. - Ser. III - Sci. Vie *323*, 1009–1017.

Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., et al. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes – a review. J. Appl. Ecol. *48*, 619–629.

Tully, K.L., Lawrence, D., and Scanlon, T.M. (2012). More trees less loss: Nitrogen leaching losses decrease with increasing biomass in coffee agroforests. Agric. Ecosyst. Environ. *161*, 137–144.

Vaast, P., Bertrand, B., Perriot, J.-J., Guyot, B., and Génard, M. (2006). Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J. Sci. Food Agric. *86*, 197–204.

Valencia, R., Balslev, H., and Paz-y-Miño-C, G. (1994). High tree alpha-diversity in Amazonian Ecuador. Biodivers. Conserv. *3*, 21–28.

Vandermeer, J., Perfecto, I., and Philpott, S. (2010). Ecological Complexity and Pest Control in Organic Coffee Production: Uncovering an Autonomous Ecosystem Service. BioScience *60*, 527–537.

Vega, F.E., Franqui, R.A., and Benavides, P. (2002a). The presence of the coffee berry borer, *Hypothenemus hampei*, in Puerto Rico: fact or fiction? J. Insect Sci. *2*, 1–3.

Vega, F.E., Rosenquist, E., and Collins, W. (2003). Global project needed to tackle coffee crisis. Nature *425*, 343–343.

Vega, M.F.D.L., Bratescu, A., Martínez, J.O., Oviedo, J.A., and Acosta, A. (2002b). Centroamérica: el impacto de la caída de los precios del café (México: Naciones Unidas Comisión Económica para América Latina y el Caribe (CEPAL)).

Villarreyna, R.A., and Avelino, J. (2016). Efecto de la sombra sobre las plagas y enfermedades, a través del microclima, fenología y estado fisiológico del cafeto (CATIE, CIRAD, Conservation International).

Vossen, H.A.M.V. der (2001). Agronomy I: Coffee Breeding Practices. In Coffee: Recent Developments, R.J. Clarke, and O.G. Vitzthum, eds. (Blackwell Science Ltd), pp. 184–201.

Waller, J.M., Bigger, M., and Hillocks, R.J. (2007). Coffee pests, diseases and their management (Egham, UK: CABI).

Weber, J., Halsall, C.J., Muir, D., Teixeira, C., Small, J., Solomon, K., Hermanson, M., Hung, H., and Bidleman, T. (2010). Endosulfan, a global pesticide: A review of its fate in the environment and occurrence in the Arctic. Sci. Total Environ. *408*, 2966–2984.

Wintgens, J.N. (2012). The Coffee Plant. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 3–60.

Wrigley, G. (1988). Coffee (Longman Scientific & Technical).

Yang, X.B. (1992). Rain Dispersal of *Colletotrichum gloeosporioides* in Simulated Rice Field Conditions. Phytopathology *82*, 1219–1222.

Zamarripa, A., and Pétiard, V. (2012). Biotechnologies Applied to Coffee. In Coffee: Growing, Processing, Sustainable Production : A Guidebook for Growers, Processors, Traders, and Researchers, (Weinheim: Jean Nicolas Wintgens), pp. 141–167.

APPENDIXES

Bachelor thesis presented by:

Kevin PIATO

In completion of the HES-SO Bachelor's degree of Science in Agronomy

Appendix 1. Environmental factors suitable for cultivation of *Coffea arabica*

Levels of suitability		*S1*		*S2*	*S3*	*N1*	*N2*
Degree of limitation		**0**	**1**	**2**	**3**	**4**	**4**
Climatic characteristics							
Temperatures (°C)	mean annual	18–20	16–18	15–16	14–15		<14
		19–20	20–22	22–24	24–26		>26
	mean maximal annual	25–26	26–28	28–30	30–32		>32
	mean daily minimal	24–25	22–24	20–22	18–20		<18
		15–17	17–19	19–21	21–23		>23
	temperature of the coldest month	14–15	10–14	7–10	4–7		<4
Rainfall (mm)	annual	1600–1800	1800–2000	2000–2200	>2200		
		1400–1500	1200–1400	1000–1200	800–1000		<800
	length of dry season (months)	2.5–3	3–4	4–5	5–6		>6
		2–2.5	1–2	0–1			
Relative humidity (%)	mean RH of driest month	50–60	60–70	70–80	80–90		>90
		50–55	40–50	30–40	20–30		<20

S1 = Best suited units with very few (three or four) slight restrictive factors or none at all.
S2 = Average units with more than three or four slight restrictive factors and/or no more than two or three moderately restrictive factors.
S3 = Marginally suitable units with more that two or three moderately restrictive factors and/or no more than one serious restrictive factor provided it does not totally exclude farming.
N1 = Unsuitable units with one or more serious restrictive factor and no more than one very serious restrictive factor which totally excludes farming. Potentially suitable if improvements were implemented.
N2 = Totally and potentially unsuitable units.

Levels of suitability		*S1*		*S2*	*S3*	*N1*	*N2*
Degree of limitation		**0**	**1**	**2**	**3**	**4**	**4**
Soil characteristics							
Slope (%)	without irrigation	0–4	4–8	8–16	16–30	30–50	>50
	with irrigation	0–2	2–4	4–8	8–16		>16
Hydrous conditions	Drainage	good	good	moderate	imperfect	poor, but drainable frequent	poor, not drainable frequent
	submersion	none	none	none	occasional		
Physical characteristics of the soil	depth of soil (cm)	>200	150–200	100–150	100–50		<50
	texture	clay clayey-silty silty-clayey	loam silty-clayey-sandy	silty-sandy	sandy-silty	sand	sand
	% of coarse elements >2 mm	0–3	3–15	15–35	35–55		>55
Chemical characteristics of the soil	pH (H_2O)	5.5–6.0	5.3–5.5	5.0–5.3	4.5–5.0	<4.5	
	apparent CEC (meq/100 g clay)	>24	16–24	<16+	<16–		
	saturation in cations of layer 0–15 cm (%)	>80	50–80	35–50	20–35	<20	
	organic carbon of layer 0–15 cm (%)	>2.4	1.2–2.4	0.8–1.2	<0.8		

(Descroix and Snoeck, 2012)

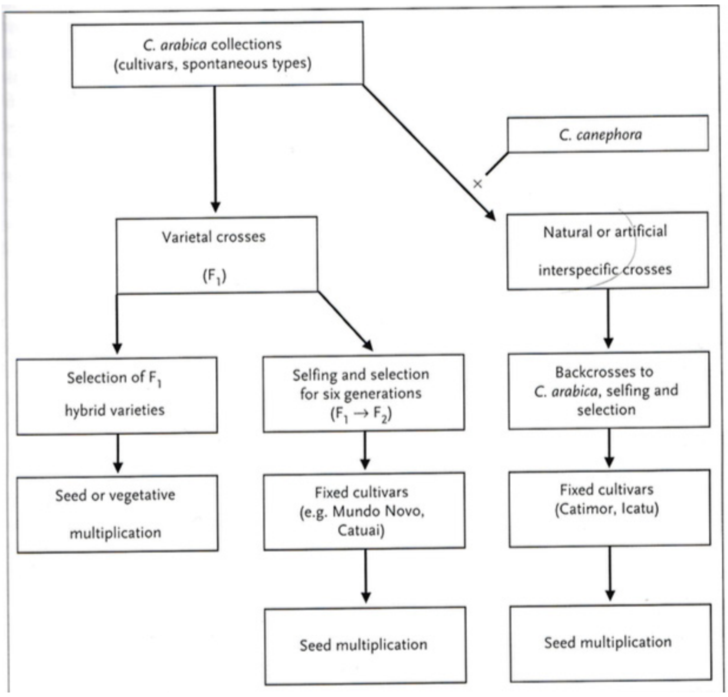
Appendix 2. Environmental factors suitable for cultivation of *Coffea canephora*

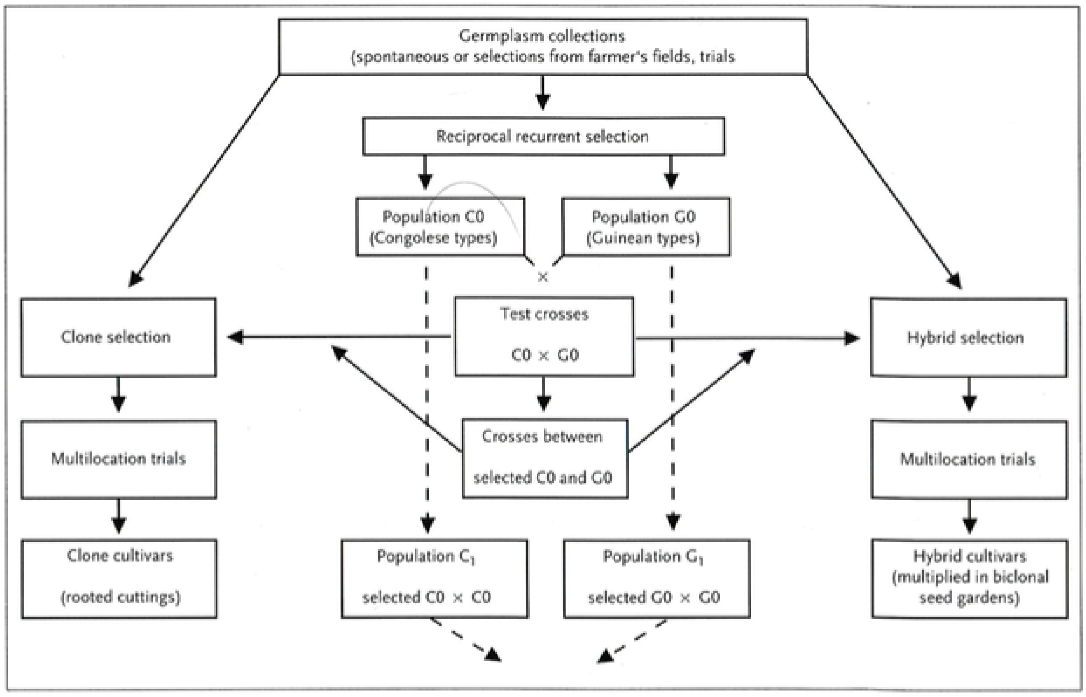
Levels of suitability		*S1*		*S2*	*S3*	*N1*	*N2*
Degree of limitation		*0*	*1*	*2*	*3*	*4*	*4*
Climatic characteristics							
Temperatures (°C)	mean annual	22–28	22–25	20–22	18–20		<18
	mean maximal annual	>29	27–29	24–27	22–24		>22
	mean daily minimal	>20	18–20	16–18	14–16		<14
Rainfall (mm)	annual	2000–2500	1600–2000	1400–1600	1200–1400		<1200
	length of dry season (months)	2–2.5	2.5–3	3–3.5	3.5–4		>4
Relative humidity (%)	mean RH of driest month	70–75	75–80	80–90	>90		
		60–65	45–60	35–45	30–35		<30

Levels of suitability		*S1*		*S2*	*S3*	*N1*	*N2*
Degree of limitation		*0*	*1*	*2*	*3*	*4*	*4*
Soil characteristics							
Slope (%)	without irrigation	0–4	4–8	8–16	16–30	30–50	>50
	with irrigation	0–2	2–4	4–8	8–16		>16
Hydrous conditions	drainage	good	good	moderate	imperfect	Imperfect, but drainable frequent	Imperfect, not drainable frequent
	submersion	none	none	none	occasional		
Physical characteristics of the soil	depth of soil (cm)	>200	150–200	100–150	50–100		<50
	texture	clay, clayey-silty, silty-clayey	loam silty-clayey-sand	silty-sandy	sandy-silty	sand	sand
	% of coarse elements > 2mm	0–3	3–15	15–35	35–55		>55
Chemical characteristics of the soil	pH (H_2O)	5.5–6.0	5.3–5.5	5.0–5.3	4.5–5.0	<4.5	
	apparent CEC (meq/100 g clay)	>16	<16+	<16–			
	saturation in cations of layer 0–15 cm (%)	>35	20–35	<20			
	organic carbon of layer 0–15 cm (%)	>1.5	0.8–1.5	<0.8			

(Descroix and Snoeck, 2012)

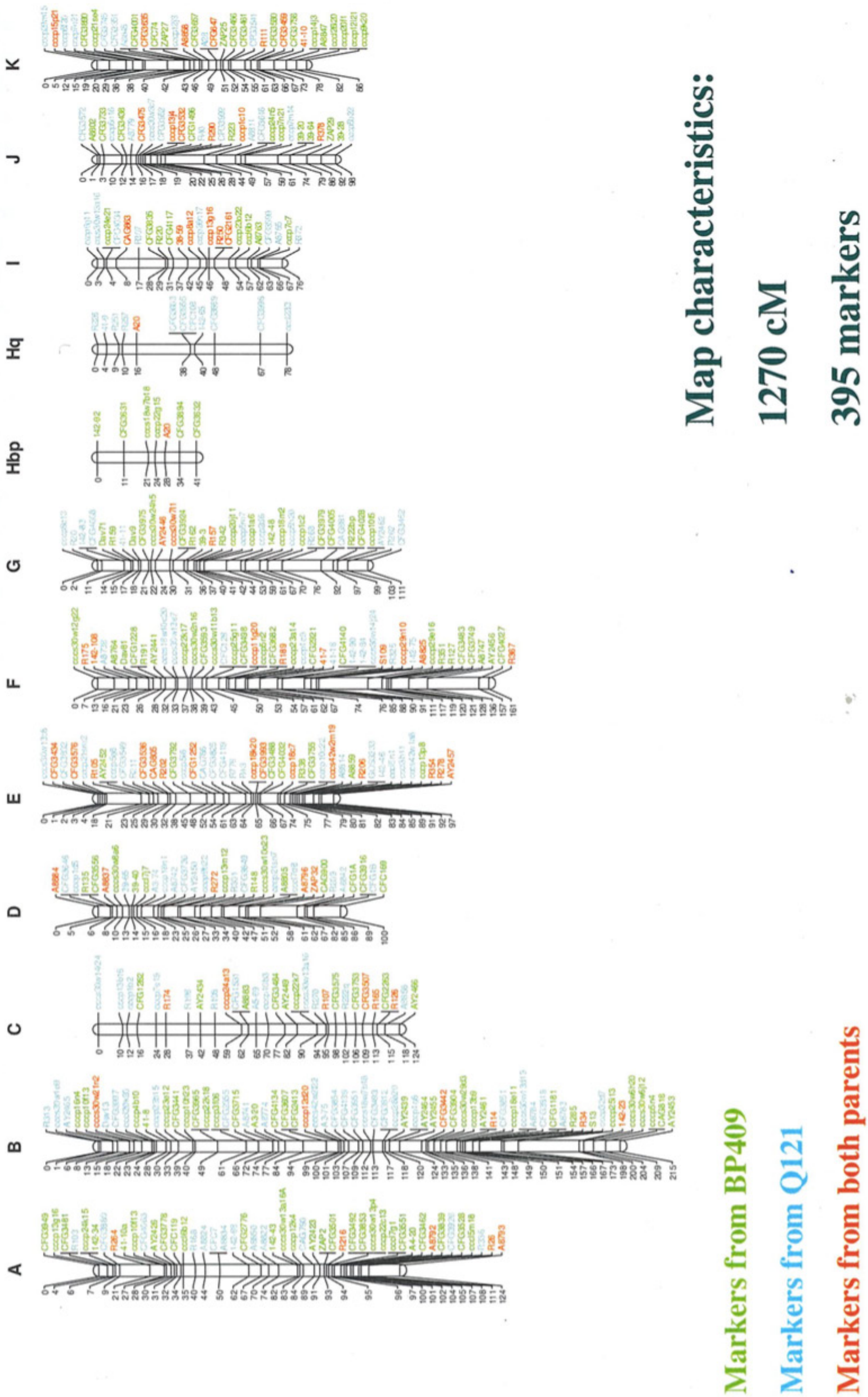
Appendix 3. Detailed breeding scheme improvement for *Coffea arabica* and *Coffea canephora*





(Eskes and Leroy, 2012)

Appendix 4. Robusta coffee genetic map



(Zamarripa and Pétiard, 2012)

Appendix 5. Soil analysis

INSTITUTO NACIONAL AUTÓNOMO DE INVESTIGACIONES AGROPECUARIAS
ESTACIÓN EXPERIMENTAL CENTRAL DE LA AMAZONÍA
CENTRO DE INVESTIGACIÓN Y CAPACITACIÓN
LABORATORIO DE SUELOS
Vía Sacha - San Carlos, Km 3 de la Parker
www.iniap.gob.ec - Correo electrónico: centralamazonia@iniap.gob.ec - Teléfono: 063700000

INFORME DE ANALISIS DE SUELOS

DATOS DEL PROPIETARIO		DATOS DE LA PROPIEDAD		DATOS DE LA MUESTRA			
Nombre	: ENSAYO SAF CAFE	Nombre	: EECA				
Dirección	: EECA (BLOQUE 400)	Provincia	: ORELLANA	Responsable Muestreo	: Cliente	Factura No.	: 0
Ciudad	: LA JOYA DE LOS SACHAS	Cantón	: LA JOYA DE LOS SACHAS	Fecha Muestreo	: 31/03/2016	Fecha Análisis	: 31/03/2016
Teléfono	: N/E	Parroquia	: SAN CARLOS	Fecha Ingreso	: 31/03/2016	Fecha Emisión	: 31/03/2016
Fax	: N/E	Ubicación	: EECA	Cultivo Actual	: RASTROJO	Fecha impresión	: 15/06/2016

			ppm		meq/100mL			ppm							%	g/cm3
Nº Laborat.	Identificación del Lote	pH	NH 4	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn	B	Cl	Humedad	Densidad Aparente
13843	13503 / T1 B1 0-40	5.31 Ac RC	34.14 M	20.57 A	0.63 A	6.50 M	1.75 M	3.98 B	11.57 A	19.18 A	285.4 A	42.60 A	0.10 B			
13844	13504 / T5 B1 0-40	5.63 MeAc	38.67 M	24.83 A	1.03 A	7.48 M	1.93 M	7.57 B	10.86 A	22.98 A	301.5 A	52.03 A	0.17 B			
13845	13505 / T9 B1 0-40	5.21 Ac RC	38.95 M	17.91 M	0.74 A	6.63 M	1.39 M	5.74 B	9.64 A	22.53 A	306.9 A	41.79 A	0.10 B			
13846	13506 / T13 B1 0-40	5.91 MeAc	32.03 M	29.68 A	0.70 A	8.64 A	2.15 A	8.90 B	8.62 A	17.96 A	225.1 A	74.08 A	0.14 B			
13847	13507 / T17 B1 0-40	5.51 MeAc	28.22 M	33.66 A	0.70 A	7.61 M	1.89 M	6.62 B	10.81 A	19.05 A	258.3 A	49.47 A	0.14 B			
13848	13508 / T2 B1 0-40	4.85 MAc RC	36.96 M	21.26 A	0.48 A	4.72 M	1.04 M	5.90 B	9.31 A	19.67 A	346.7 A	66.83 A	0.18 B			
13849	13509 / T6 B1 0-40	5.65 MeAc	24.93 M	21.64 A	0.81 A	8.79 A	1.65 M	11.37 M	11.51 A	22.76 A	273.3 A	23.97 A	0.13 B			
13850	13510 / T10 B1 0-40	5.20 Ac RC	33.26 M	24.59 A	0.77 A	6.34 M	1.63 M	9.47 B	12.91 A	24.10 A	242.7 A	36.33 A	0.37 B			
13851	13511 / T14 B1 0-40	5.35 Ac RC	31.89 M	29.24 A	0.67 A	7.17 M	1.71 M	7.09 B	11.90 A	21.21 A	301.8 A	27.62 A	0.16 B			
13852	13512 / T18 B1 0-40	5.57 MeAc	23.53 M	43.76 A	0.81 A	7.63 M	1.89 M	4.53 B	11.77 A	22.40 A	319.5 A	22.38 A	0.25 B			
13853	13513 / T3 B1 0-40	5.00 MAc RC	38.12 M	15.41 M	0.62 A	5.89 M	1.20 M	9.21 B	9.96 A	18.66 A	323.7 A	75.54 A	0.30 B			
13854	13514 / T7 B1 0-40	5.44 Ac RC	32.59 M	28.01 A	0.64 A	6.69 M	1.49 M	13.33 M	12.99 A	20.37 A	318.4 A	48.70 A	0.10 B			
13855	13515 / T11 B1 0-40	5.51 MeAc	25.96 M	23.95 A	0.80 A	7.30 M	1.85 M	9.79 B	11.60 A	22.95 A	272.9 A	34.17 A	0.13 B			
13856	13516 / T15 B1 0-40	5.52 MeAc	21.69 M	19.93 M	0.88 A	7.15 M	1.79 M	6.64 B	10.60 A	23.53 A	282.6 A	25.35 A	0.17 B			
13857	13517 / T19 B1 0-40	5.43 Ac RC	46.75 A	27.51 A	0.58 A	7.10 M	1.77 M	6.68 B	10.20 A	20.76 A	284.7 A	76.44 A	0.17 B			
13858	13518 / T4 B1 0-40	5.71 MeAc	21.20 M	25.92 A	0.70 A	8.10 A	1.64 M	12.62 M	12.76 A	20.33 A	263.9 A	24.91 A	0.15 B			
13859	13519 / T8 B1 0-40	5.46 Ac RC	26.33 M	16.09 M	0.73 A	7.59 M	1.92 M	6.11 B	11.33 A	21.77 A	257.6 A	33.43 A	0.19 B			
13860	13520 / T12 B1 0-40	5.37 Ac RC	19.82 B	21.56 A	0.77 A	7.06 M	1.86 M	8.32 B	10.90 A	23.03 A	253.2 A	22.84 A	0.10 B			

Interpretación				
NH4, P, K, Ca, Mg, S Zn, Cu, Fe, Mn, B, Cl	pH			
B = Bajo	MAc	= Muy Acido	N	= Neutro
M = Medio	Ac	= Acido	LAl	= Lig. Alcalino
A = Alto	MeAc	= Med. Acido	MeAl	= Med. Alcalino
	LAc	= Lig. Acido	Al	= Alcalino
	PN	= Prac. Neutro	RC	= Requiere Cal

Determinación	Metodología	Extractante
NH 4, P	Colorimetría	Olsen
K, Ca, Mg	Absorción	Modificado
Zn, Cu, Fe, Mn	Atómica	pH 8.5
S	Turbidimetría	Fosfato de Ca
B	Colorimetría	Monobásico
Cl	Volumetría	Pasta Saturada
pH	Potenciométrica	Suelo: agua (1:2,5)

Niveles de Referencia								
NH 4	20 -	40	Mg	1,0 -	2	Fe	20 -	40
P	10 -	20	S	10 -	20	Mn	5 -	15
K	0,2 -	0,4	Zn	2,0 -	7,0	B	0,5 -	1,0
Ca	4 -	8	Cu	1,0 -	4,0	Cl	17 -	34

Responsable Laboratorio

Analista

N/E = No entregado
<LC = Menor al Límite de Cuantificación
Los resultados emitidos en este informe, corresponden únicamente a la(s) muestra(s) sometida(s) al ensayo
Se prohibe la reproducción parcial, si se va a copiar que sea en su totalidad

Formato1 Página1

DATOS DEL PROPIETARIO		DATOS DE LA PROPIEDAD		DATOS DE LA MUESTRA			
Nombre	: ENSAYO SAF CAFE	Nombre	: EECA				
Dirección	: EECA (BLOQUE 400)	Provincia	: ORELLANA	Responsable Muestreo	: Cliente	Factura No.	: 0
Ciudad	: LA JOYA DE LOS SACHAS	Cantón	: LA JOYA DE LOS SACHAS	Fecha Muestreo	: 31/03/2016	Fecha Análisis	: 31/03/2016
Teléfono	: N/E	Parroquia	: SAN CARLOS	Fecha Ingreso	: 31/03/2016	Fecha Emisión	: 31/03/2016
Fax	: N/E	Ubicación	: EECA	Cultivo Actual	: RASTROJO	Fecha impresión	: 15/06/2016

			ppm		meq/100mL			ppm							%	g/cm3
Nº Laborat.	Identificación del Lote	pH	NH 4	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn	B	Cl	Humedad	Densidad Aparente
13861	13521 / T16 B1 0-40	5.75 MeAc	16.97 B	24.17 A	0.79 A	7.76 M	1.68 M	7.97 B	11.96 A	231.3: A	269.9 A	23.27 A	0.31 B			
13862	13522 / T20 B1 0-40	5.70 MeAc	18.22 B	21.44 A	0.88 A	8.48 A	2.06 A	7.59 B	9.85 A	22.45 A	238.5 A	43.98 A	0.12 B			

Interpretación				
NH4, P, K, Ca, Mg, S Zn, Cu, Fe, Mn, B, Cl	pH			
B = Bajo	MAc	= Muy Acido	N	= Neutro
M = Medio	Ac	= Acido	LAl	= Lig. Alcalino
A = Alto	MeAc	= Med. Acido	MeAl	= Med. Alcalino
	LAc	= Lig. Acido	Al	= Alcalino
	PN	= Prac. Neutro	RC	= Requiere Cal

Determinación	Metodología	Extractante
NH 4, P	Colorimetría	Olsen
K, Ca, Mg	Absorción	Modificado
Zn, Cu, Fe, Mn	Atómica	pH 8.5
S	Turbidimetría	Fosfato de Ca
B	Colorimetría	Monobásico
Cl	Volumetría	Pasta Saturada
pH	Potenciométrica	Suelo: agua (1:2,5)

Niveles de Referencia								
NH 4	20 -	40	Mg	1,0 -	2	Fe	20 -	40
P	10 -	20	S	10 -	20	Mn	5 -	15
K	0,2 -	0,4	Zn	2,0 -	7,0	B	0,5 -	1,0
Ca	4 -	8	Cu	1,0 -	4,0	Cl	17 -	34

Responsable Laboratorio

Analista

N/E = No entregado
<LC = Menor al Límite de Cuantificación
Los resultados emitidos en este informe, corresponden únicamente a la(s) muestra(s) sometida(s) al ensayo
Se prohibe la reproducción parcial, si se va a copiar que sea en su totalidad

Formato1 Página2

INIAP-Estación Experimental Central Amazónica

INSTITUTO NACIONAL AUTÓNOMO DE INVESTIGACIONES AGROPECUARIAS
ESTACIÓN EXPERIMENTAL CENTRAL DE LA AMAZONÍA
CENTRO DE INVESTIGACIÓN Y CAPACITACIÓN
LABORATORIO DE SUELOS
Vía Sacha - San Carlos, Km 3 de la Parker
www.iniap.gob.ec - Correo electrónico: centralamazonia@iniap.gob.ec - Teléfono: 063700000

Instituto Nacional Autónomo de Investigaciones Agropecuarias

INFORME DE ANALISIS DE SUELOS

DATOS DEL PROPIETARIO		DATOS DE LA PROPIEDAD		DATOS DE LA MUESTRA			
Nombre	ENSAYO SAF CAFE	Nombre	EECA	Informe No.			
Dirección	EECA (BLOQUE 400)	Provincia	ORELLANA	Responsable Muestreo	Cliente	Factura No.	0
Ciudad	LA JOYA DE LOS SACHAS	Cantón	LA JOYA DE LOS SACHAS	Fecha Muestreo	31/03/2016	Fecha Análisis	31/03/2016
Teléfono	N/E	Parroquia	SAN CARLOS	Fecha Ingreso	31/03/2016	Fecha Emisión	31/03/2016
Fax	N/E	Ubicación	EECA	Cultivo Actual	RASTROJO	Fecha Impresión	15/06/2016

		Textura (%)			Clase Textural	meq/100mL			dS/m	(%)	meq/100mL	Ca	Mg	Ca+Mg	meq/100g
Nº Laborat.	Identificación	Arena	Limo	Arcilla		Al+H	Al	Na	C.E.	M.O.	Σ Bases	Mg	K	K	C.I.C
13843	13503 / T1 B1 0-40	28	31	41	Arcilloso	0.90 LT				2.30 B	8.88	3.71 M	2.78 M	13.10 M	
13844	13504 / T5 B1 0-40	28	29	43	Arcilloso	0.80 LT				2.30 B	10.44	3.88 M	1.87 B	9.14 B	
13845	13505 / T9 B1 0-40	34	27	39	Franco-Arcilloso	1.00 LT	0.50 LT			3.00 B	8.76	4.77 M	1.88 B	10.84 B	
13846	13506 / T13 B1 0-40	30	27	43	Arcilloso	0.50 Ad				1.50 B	11.49	4.02 M	3.07 M	15.41 M	
13847	13507 / T17 B1 0-40	26	27	47	Arcilloso	0.80 LT				2.60 B	10.20	4.03 M	2.70 M	13.57 M	
13848	13508 / T2 B1 0-40	35	25	39	Franco-Arcilloso	2.00 T	0.40 LT			2.60 B	6.24	4.54 M	2.17 B	12.00 B	
13849	13509 / T6 B1 0-40	28	27	45	Arcilloso	0.80 LT				3.00 B	11.25	5.33 M	2.04 B	12.89 M	
13850	13510 / T10 B1 0-40	36	23	41	Arcilloso	1.40 LT	0.70 LT			3.00 B	8.74	3.89 M	2.12 B	10.35 B	
13851	13511 / T14 B1 0-40	28	25	47	Arcilloso	0.80 LT				2.60 B	9.55	4.19 M	2.55 M	13.25 M	
13852	13512 / T18 B1 0-40	26	29	45	Arcilloso	0.80 LT				1.90 B	10.33	4.04 M	2.33 B	11.75 B	
13853	13513 / T3 B1 0-40	28	32	40	Franco-Arcilloso	1.70 T	0.70 LT			1.90 B	7.71	4.91 M	1.94 B	11.44 B	
13854	13514 / T7 B1 0-40	30	28	42	Arcilloso	1.10 LT	0.60 LT			2.60 B	8.82	4.49 M	2.33 B	12.78 M	
13855	13515 / T11 B1 0-40	30	26	44	Arcilloso	0.70 LT				1.90 B	9.95	3.95 M	2.31 B	11.44 B	
13856	13516 / T15 B1 0-40	30	22	48	Arcilloso	0.70 LT				2.30 B	9.82	3.99 M	2.03 B	10.16 B	
13857	13517 / T19 B1 0-40	32	28	40	Franco-Arcilloso	0.60 LT				2.30 B	9.45	4.01 M	3.05 M	15.29 M	
13858	13518 / T4 B1 0-40	32	26	42	Arcilloso	0.70 LT				2.30 B	10.44	4.94 M	2.34 B	13.91 M	
13859	13519 / T8 B1 0-40	30	26	44	Arcilloso	0.80 LT				3.00 B	10.24	3.95 M	2.63 M	13.03 M	
13860	13520 / T12 B1 0-40	30	24	46	Arcilloso	0.90 LT				2.30 B	9.69	3.80 M	2.42 B	11.58 B	
13861	13521 / T16 B1 0-40	26	28	46	Arcilloso	0.50 Ad				2.30 B	10.23	4.62 M	2.13 B	11.95 B	

Interpretación	
Al+H, Al, Na	C.E.
Ad = Adecuado	NS = No Salino
LT = Ligeram. Tóxico	LS = Lig. Salino
T = Tóxico	S = Salino
	MS = Muy Salino

Abreviaturas	
C.E.	Conductividad Eléctrica
M.O.	Materia Orgánica
CIC	Capacidad de Intercambio Catiónico

Determinación	Metodología	Extractante
M.O.	Walkey Black	Dicromato de K
C.I.C.		Acetato de Amonio
Na		Cloruro de Bario
C.E.	Extracto de pasta saturada	Agua

Niveles de Referencia					
Lig. Tóxico meq/100mL		Lig. Salino (dS/m)		Medio	
Al + H	0.51 - 1.50	C.E.	2.0 - 4.0	Ca/Mg	2.0 - 8.0
Al	0.31 - 1.00	Medio (%)		Mg/K	2.5 - 10.0
Na	0.5 - 1.0	M.O.	3.1 - 5.0	(Ca+Mg)/K	12.5 - 50.0

Responsable Laboratorio

Laboratorista

N/E = No entregado
<LC = Menor al Límite de Cuantificación
Los resultados emitidos en este informe, corresponden únicamente a la(s) muestra(s) sometida(s) al ensayo.
Se prohibe la reproducción parcial, si se va a copiar que sea en su totalidad

Formato 2 Págin1

DATOS DEL PROPIETARIO		DATOS DE LA PROPIEDAD		DATOS DE LA MUESTRA			
Nombre	ENSAYO SAF CAFE	Nombre	EECA	Informe No.			
Dirección	EECA (BLOQUE 400)	Provincia	ORELLANA	Responsable Muestreo	Cliente	Factura No.	0
Ciudad	LA JOYA DE LOS SACHAS	Cantón	LA JOYA DE LOS SACHAS	Fecha Muestreo	31/03/2016	Fecha Análisis	31/03/2016
Teléfono	N/E	Parroquia	SAN CARLOS	Fecha Ingreso	31/03/2016	Fecha Emisión	31/03/2016
Fax	N/E	Ubicación	EECA	Cultivo Actual	RASTROJO	Fecha Impresión	15/06/2016

		Textura (%)			Clase Textural	meq/100mL			dS/m	(%)	meq/100mL	Ca	Mg	Ca+Mg	meq/100g
Nº Laborat.	Identificación	Arena	Limo	Arcilla		Al+H	Al	Na	C.E.	M.O.	Σ Bases	Mg	K	K	C.I.C
13862	13522 / T20 B1 0-40	36	24	40	Franco-Arcilloso	0.50 Ad				2.30 B	11.42	4.12 M	2.34 B	11.98 B	

Interpretación	
Al+H, Al, Na	C.E.
Ad = Adecuado	NS = No Salino
LT = Ligeram. Tóxico	LS = Lig. Salino
T = Tóxico	S = Salino
	MS = Muy Salino

Abreviaturas	
C.E.	Conductividad Eléctrica
M.O.	Materia Orgánica
CIC	Capacidad de Intercambio Catiónico

Determinación	Metodología	Extractante
M.O.	Walkey Black	Dicromato de K
C.I.C.		Acetato de Amonio
Na		Cloruro de Bario
C.E.	Extracto de pasta saturada	Agua

Niveles de Referencia					
Lig. Tóxico meq/100mL		Lig. Salino (dS/m)		Medio	
Al + H	0.51 - 1.50	C.E.	2.0 - 4.0	Ca/Mg	2.0 - 8.0
Al	0.31 - 1.00	Medio (%)		Mg/K	2.5 - 10.0
Na	0.5 - 1.0	M.O.	3.1 - 5.0	(Ca+Mg)/K	12.5 - 50.0

Responsable Laboratorio

Laboratorista

N/E = No entregado
<LC = Menor al Límite de Cuantificación
Los resultados emitidos en este informe, corresponden únicamente a la(s) muestra(s) sometida(s) al ensayo.
Se prohibe la reproducción parcial, si se va a copiar que sea en su totalidad

Formato 2 Págin2

INIAP-Estación Experimental Central Amazónica

Appendix 6. Soil profiles in the EECA experimental field

(Source: Kevin Piato)

Appendix 7. Field data sheet for PDD assessment

Evaluación de variables sanitarias SAF CAFÉ

Fecha: ______________________ Evaluadores: ______________________

TR=Total de Ramas / **TAL**=Ramas Taladro / **TF**=Total de Frutos / **FB**=Frutos Brocados / **BEA**=Frutos Beauveria

TH=Total de Hojas / **ANT**=Antracnosis / **PHO**=Phoma / **MH**= Mancha de hierro / **HIL**= Mal de Hilachas / **MIN**=Minador

PARC	MAN	SOM	Plant	TR	TAL	FR Rama Baja			FR Rama Media			Rama Baja						Rama Media						Rama Alta					
						TF	FB	BEA	TF	FB	BEA	TH	ANT	PHO	MH	HIL	MIN	TH	ANT	PHO	MH	HIL	MIN	TH	ANT	PHO	MH	HIL	MIN
101	AC	SOL	40																										
101	AC	SOL	43																										
101	AC	SOL	45																										
101	AC	SOL	54																										
101	AC	SOL	65																										
101	AC	SOL	77																										
101	AC	SOL	78																										
101	AC	SOL	88																										
101	AC	SOL	105																										
102	AC	BÁL	41																										
102	AC	BÁL	45																										
102	AC	BÁL	55																										
102	AC	BÁL	56																										
102	AC	BÁL	65																										
102	AC	BÁL	66																										
102	AC	BÁL	69																										
102	AC	BÁL	88																										
102	AC	BÁL	90																										
103	AC	GUA	79																										
103	AC	GUA	80																										
103	AC	GUA	81																										
103	AC	GUA	103																										
103	AC	GUA	90																										
103	AC	GUA	104																										
103	AC	GUA	93																										
103	AC	GUA	45																										
103	AC	GUA	88																										
104	AC	ERY	104																										
104	AC	ERY	88																										
104	AC	ERY	69																										
104	AC	ERY	100																										
104	AC	ERY	78																										
104	AC	ERY	101																										
104	AC	ERY	45																										
104	AC	ERY	76																										
104	AC	ERY	93																										